THE CALIBRATION OF COMPOUND CRUMP AND SHARP-CRESTED GAUGING WEIRS IN SOUTH AFRICA

by

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DECLARATION

I the undersigned hereby declare that the work contained in this dissertation is my own original work and has not previously in its entirety or in part been submitted at any university for a degree.

Signature :

Date :

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SYNOPSIS

The present network of flow gauging stations in South Africa has grown from isolated observations on an ad hoc basis to an extensive network of stations across the country. Standardised gauging stations to suit local conditions have been developed which include purposely designed compound weirs.

Nearly all compound gauging weirs in South Africa have, for practical reasons, been constructed without dividing walls, thus deviating from the standards set by the British Standards Institution (1981). Uncertainty about the accuracy of calibration of such structures had to be clarified and, where necessary, adjustments had to be made to existing calibration formulae in order to compensate for the deviations. It was also necessary to determine whether the accuracies that could be attained were adequate in terms of the potential financial implications of inaccuracies. It has thus become necessary to re-evaluate the calibration of these structures which consist of mainly compound Crump and sharp-crested weirs.

Selected flow records were analysed and the data was used to determine the impact of errors on the required capacities of reservoirs. This was done in an attempt to provide guidelines for the accuracy required in flow records.

Analysing a single application of a flow record cannot provide guidelines for the required accuracy of a flow record and thus the gauging of flow. Although no general conclusions can be drawn, it appears that the benefits arising from an improvement in the accuracy of a flow record are proportionally greater than the percentage improvement in accuracy.

Three-dimensional flow conditions exist either upstream or downstream of the point of stage measurement depending on the presence or absence of dividing walls at a compound gauging weir. The existing calibration theory does not account for the influences of three-dimensional flow conditions and associated energy losses in the determination of the upstream total energy head. Hydraulic model tests were thus undertaken to determine the magnitude of the resulting energy losses. New techniques were developed to compensate for these energy losses in the calibration theory of compound gauging weirs.

Application of the new calculation techniques to rate compound weirs using a single point of stage measurement results in improvements in accuracy. It was found that compound weirs

without dividing walls can be rated to greater levels of accuracy than weirs with dividing walls, where stage measurements are taken at a single point.

SAMEVATTING

Die huidige netwerk van vloeimeetpunte in Suid-Afrika het gegroei van geïsoleerde waarnemings op 'n ad hoc basis, tot 'n uitgebreide netwerk van meetpunte versprei oor die hele land. Standaard meetstruktuure aangepas vir plaaslike omstandighede is ontwikkel en sluit in doelgeboude saamgestelde meetstrukture.

Bykans alle saamgestelde meetstrukture in Suid-Afrika is weens praktise oorwegings opgerig sonder verdeelmure, wat afwyk van die standaarde gestel deur die British Standards Institution (1981). Onsekerhede aangaande die akkuraatheid van die kalibrasie van sulke strukture moes opgeklaar word en aanpassings aan die bestaande teorie moes gedoen word om hiervoor te kompenseer, indien nodig. Dit was ook nodig om vas te stel of akkuraathede wat haalbaar is voldoende is, met inagneming van potensiële finansiële implikasies van onakkuraathede. Dit het dus nodig geword om die bestaande kalibrasie van saamgestelde meetstrukture, hoofsaaklik Crump en skerpkruin meetwalle, te her-evalueer.

Sekere vloeirekords is ontleed en die data is gebruik om die impak van foute te bepaal op die berekende kapasiteite van opgaardamme. Dit is gedoen in 'n poging om riglyne neer te lê rakende die akkuraatheid verlang in 'n vloeirekord.

Die ontleding van 'n enkele toepassing van 'n vloeirekord lewer nie genoegsame data om riglyne vas te stel vir die verlangde akkuraatheid van 'n vloeirekord of vloeimeting nie. Alhoewel geen duidelike riglyne hieruit voortspruit nie, kom dit voor asof die voordele verkry uit 'n verbetering in die akkuraatheid van 'n vloeirekord in verhouding groter is as die vermindering in die vloeimetingsfout.

Drie-dimensionele vloeitoestande bestaan of stroomop of stroomaf van die punt van watervlakmeting, afhangende van die teenwoordigheid of afwesigheid van verdeelmure by 'n saamgestelde meetstruktuur. Die bestaande kalibrasieteorie maak nie voorsiening vir die invloed van drie-dimensionele vloeitoestande en die gepaardgaande energieverliese op die bepaling van die totale stroomop energiehoogte nie. Hidrouliese modeltoetse is onderneem om die omvang van die resulterende energieverliese vas te stel. Nuwe tegnieke in die kalibrasieteorie vir saamgestelde strukture is ontwikkel om te kompenseer vir hierdie energieverliese.

'n Verbetede akkuraatheid word verkry wanneer die nuwe tegniek toegepas word op die kalibrasie van saamgestelde meetstrukture met 'n enkele punt van watervlakmeting. Daar is gevind dat saamgestelde meetstrukture sonder verdeelmure akkurater gekalibreer kan word, as strukture met verdeelmure waar watervlakke slegs by 'n enkele punt gemeet word.

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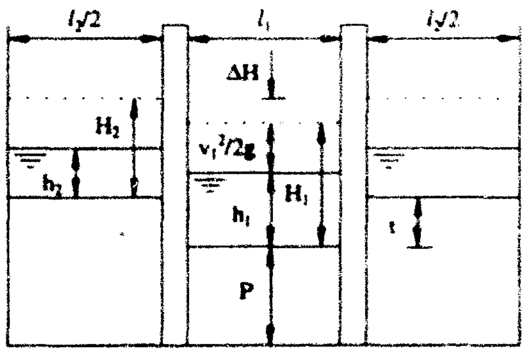
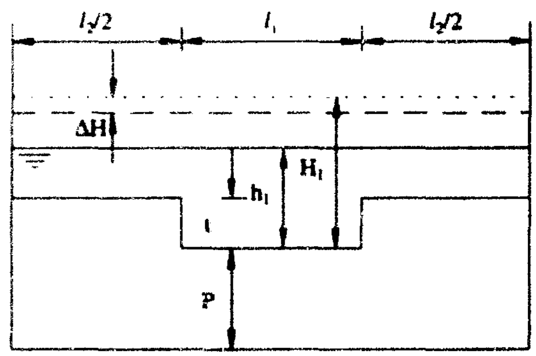


Compound weir with dividing walls.



Compound weir without dividing walls.

Definition sketch

A	:	**Flow cross section normal to the direction of flow (m^2).**
A_l	:	**Flow cross section in front of low notch of weir (m^2).**
B	:	**Surface width of flow section in natural channel (m).**
C_d	:	**Discharge coefficient (Crump and IMFT formulae).**
C_p	:	**Discharge coefficient (Department of Water Affairs and Forestry formulae).**
Fr	:	**Froude number** $\left(=\sqrt{\frac{Q^2B}{gA^3}}\right)$.
f	:	**Correction coefficient for submerged flow conditions.**
g	:	**Acceleration due to gravity** $\left(9{,}81\,m/s^2\right)$.
h	:	**Gauged head or head upstream of a structure (m).**
h_l	:	**Head relative to low notch level of a compound weir (m).**
h_2	:	**Head relative to high notch level or submergence head (m).**
h_c	:	**Critical flow depth (m).**
h_x	:	**Gauged head corrected for systematic error in measurements (m).**
H	:	**Total energy head relative to weir crest** $\left(= h + {v^2}/{2g}\right)$.
H_l	:	Total energy head relative to low notch level of a compound weir (m).
H_2	:	Total energy head relative to high notch level or total head downstream of weir (m).
ΔH	:	Difference in upstream total energy head or correction in calculated total energy head (m).

H_{max} : Maximum total energy head (m).

H_x : Total energy head corrected for systematic error in measured head (m).

$k_{1,2,m}$: Coefficients used to determine losses.

l : Length of a weir crest or width of a canal (m).

l_1 : Length of the low notch of a compound weir (m).

l_2 : Length of the high notch of a compound weir (m).

P : Upstream pool depth (m).

p : Pressure (N/m^2).

Q : Discharge (m^3/s).

Q_1 : Discharge confined to low notch of compound weir (m^3/s).

Q_2 : Discharge confined to high notch of compound weir (m^3/s).

Q_{cx} : Calculated discharge allowing for systematic error in measurements (m^3/s).

Q_{ck} : Calculated discharge with improved calculation methods, for compound weirs with dividing walls (m^3/s).

$Q_{\Delta H}$: Calculated discharge with improved calculation methods, for compound weirs without dividing walls (m^3/s).

Q_m : Discharge as measured in model (m^3/s).

Q_t : Theoretical discharge (m^3/s).

v : Flow velocity (m/s)

v_1 : Flow velocity upstream of low notch of weir (m/s).

v_2 : Flow velocity upstream of high notch of weir or downstream of weir (m/s).

v_c : Critical flow velocity (m/s).

Z : Height above datum (m).

ρ : Fluid density (kg/m^3).

THE CALIBRATION OF COMPOUND CRUMP AND SHARP-CRESTED GAUGING WEIRS IN SOUTH AFRICA

1. INTRODUCTION.

Water is essential to all forms of life and is thus the most precious of all the natural resources. The planning and control of rational water use require accurate measurement of the availability of this resource. Despite careful planning, the successful development of a region is likely to fail without adequate and reliable hydrological data. This is particularly so in relatively dry countries like the Republic of South Africa.

Hydrological data is frequently used to determine the capacity of a reservoir required to supply a certain demand of water for domestic, industrial or any other usage. Flood damage could be reduced considerably if the design of structures in river channels, for example weirs, and any land use in flood plains were to be based on accurate hydrological data. Hydrological data is also used to determine flood discharges to size spillways of reservoirs, or the height of bridges above riverbeds.

The gathering of hydrological data in the Republic of South Africa is the responsibility of the Directorate of Hydrology in the Department of Water Affairs and Forestry (DWAF). DWAF requires this information in order to perform its task of developing and managing the water resources of South Africa.

It is generally known that runoff is a function of precipitation characteristics: - duration, intensity and areal extent. It is, however, also a function of catchment characteristics: - vegetation, land use, soil type, geology and topography. The management, development and control of water resources require accurate and reliable stream flow information, which can be in the format of discharge or stage. Information of this nature can only be obtained from a well established, operated and maintained network of flow gauging stations.

A flow gauging station may be defined as follows:

> *"A gauging station is a site on a river which has been selected, equipped and operated to provide the basic data from which systematic records of water level and discharge may be derived. Essentially it consists of a natural or artificial river cross-section where a continuous record of stage can be obtained and where a relation between stage and discharge can be determined."* (Lambie, 1978).

From this definition it is obvious that two actions are required to measure discharge; the gauging of stage, and the derivation of discharge from stage records. Various methods are used by DWAF to convert stage records into discharge or flow records. Direct measurement techniques include the use of flow gauging weirs and velocity-area methods, whilst indirect measurements are used mainly to determine peak discharges after flood events. By combining both methods a wide ranging flow record at a point of interest can be produced.

Flow in South African rivers is monitored at roughly 800 gauging stations. At approximately 80% of these stations flows are gauged with compound Crump or sharp-crested weirs. Compound gauging weirs are used in an attempt to ensure accurate gauging and sensitivity over a wide range of discharges in rivers. A compound gauging weir consists of a series of individual weirs, with the crest of each weir at a different level across the width of a stream. Low discharges in a river flow only over the lowest crest, or the low notch, of a compound weir and with increasing discharge more notches start to operate.

Theory and coefficients to rate Crump and sharp-crested weirs are well established for two-dimensional flow conditions, which exist in weirs with only a single crest section (Ackers, et al., 1978). According to the British Standards Institution, (BSI, 1981), the individual weir sections of a compound gauging weir should be separated by dividing walls to minimise the effect of three-dimensional flow conditions[1]. BSI (1981) recommends that normal two-dimensional discharge formulae should be used to rate the individual weir sections of a compound weir.

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[1] Three-dimensional flow conditions are defined in this thesis as flows with three, mutually perpendicular, velocity components. Two-dimensional flow conditions have no horizontal velocity component parallel to the weir crest.

As a result of practical and economic considerations the majority of compound gauging structures in South Africa have been constructed without any dividing walls. From a practical point of view, high flows often bring down debris that become entangled around the walls, adversely affecting the rating. In addition to the absence of dividing walls, it is also common practice in South Africa to monitor upstream water levels only in the vicinity of the lowest crest or notch of a compound weir. Doubt has been expressed, within DWAF, about the accuracy of ratings of compound weirs due to the above mentioned practices and especially due to the requirement set by the BSI that compound weirs without dividing walls need in situ or model calibrations.

The aims of this thesis are:

- the establishment of standards for the required accuracies of flow records and therefore flow measurement in general,
- to determine if compound gauging structures built without dividing walls can be theoretically calibrated to the same accuracies as those with dividing walls and whether model studies are required for these calibrations,
- whether it is necessary to construct dividing walls at existing compound structures,
- to clarify the uncertainties surrounding the calibration theory for thin-plate weirs in use by DWAF and
- to improve calibration theory for compound gauging weirs with and without dividing walls, if necessary.

2. THE DEVELOPMENT OF FLOW GAUGING IN SOUTH AFRICAN RIVERS.

Except for the documentation of historical flood events, information on the history of flow gauging in South African rivers prior to 1900 is scarce. This is especially true regarding techniques used to gauge discharge in rivers. It is probably due to the disastrous nature of floods and their impression on mankind, that earlier historical information on flood events is available at all.

The first documented flood event in South Africa occurred shortly after the arrival of Jan van Riebeeck at the Cape of Good Hope. This event took place during the night of 22 July 1652 when an extremely heavy downpour was experienced. The rain storm was so intense that on the morning of 23 July rivers were not capable of handling the runoff and flooded the land (Thom, 1952). Flood waters from the Vars River inundated the newly established vegetable garden and all the crops were destroyed.

In 1822 a flood in the Olifants river near Clanwilliam was observed during which the water level rose 29 feet ($\approx$9m) above the normal stage of the river (Linscott, 1924). Estimations of discharge, as opposed to stage, are first documented for the 18 May 1859 flood observed in the lower reaches of the Olifants river. A peak discharge of 25 000 cusecs (710m^3/s), compared to the four cusecs (0,110 m^3/s) of the previous day, was estimated
(Linscott, 1924).

Historical drought sequences are also mentioned in literature, but this information is usually limited to periods of zero flow in rivers. Observations of flow in the Kariega River, Eastern Cape, were made, probably on a daily basis, as early as 1860. Prior to 1860 a stream of water flowed daily in the Kariega River from October to May without failure. Similar flow conditions were observed from December to May for the years 1861 to 1863. The river gradually dried up and subsequent to 1880 flow only occurred after substantial rainfall in the catchment (Linscott, 1924).

The first long-term documented daily stage recording in the country started during July 1885 at the pumping station of the Kimberley Water Works Company in the Vaal River at

Riverton (Hurley, 1905). At the beginning of 1909 DWAF assumed the responsibility for these measurements. According to available records, the only other gauging station operational earlier than 1900 was established in 1898 in the Breede River near Robertson. Stage measurements at this gauging station ceased during 1917.

The most elementary method to measure stage in a river is the observation of water levels against fixed gauge plates on the river bank. Continuous records of stage in streams are obtained by means of automatic water level recorders. In South Africa mechanical recorders have been widely used for the continuous recording of stage. These mechanical recorders consist of a rotating horizontal drum driven by a clockwork mechanism. The drum rotates once in a week, or month, depending on the settings of the clockwork mechanism. A pen attached to a float and counterweight traces the stage variations in the river on graph paper wrapped around the drum. The graph paper is replaced after each full revolution of the drum.

The first mechanical recorder was installed on 1 December 1900 at hydrological gauging station, C2H010, on the Vaal River at Rietfontein near Vereeniging (Department of Water Affairs, 1990). Observations at this station continued until 30 September 1922. The oldest operational gauging station equipped with a mechanical recorder, is that on the Pienaars River at Klipdrift, A2H006, where recording started on 1 March 1905.

The first gauging weirs completed specifically to measure flow in rivers in South Africa were completed in 1904 in the Transvaal (Menné, 1960). New structures were constructed until 1916 when a lack of funds due to the First World War brought a temporary halt to the expansion of the gauging network. At that time there were at least seventeen compound gauging weirs established in the Transvaal by the former Irrigation Department, where discharges in rivers were gauged continuously with mechanical recorders. Besides these weirs, several other gauging stations were established during 1915 by the Rand Water Board under supervision of the Government. In the Cape Province at least eight compound gauging weirs had been established and in the Orange Free State at least three compound gauging weirs were operational (Kanthack, 1924). **Table 2.1** gives details of the first compound gauging weirs built in each original province of South Africa; all these weirs were sharp-crested structures.

NUMBER	RIVER	PLACE	OPENED	CLOSED	PROVINCE
A2H001	KROKODIL	HARTBEESPOORT	1904 08 01	1922 09 30	TVL
A2H002	MAGALIES	HARTBEESPOORT	1904 08 01	1922 09 30	TVL
C2H001	MOOI	WITRAND	1904 08 01		TVL
D3H001	SEEKOEI	HAASFONTEIN	1911 10 01	1941 04 30	CAPE
J2H001	GAMKA	KLIPFONTEIN	1911 11 05	1921 01 31	CAPE
J2H002	NELS	BUFFELS VALLEI	1911 12 06	1918 09 30	CAPE
C6H001	VALS	ROODEWAL	1913 01 15		OFS
C8H001	WILGE	FRANKFORT	1913 10 01		OFS
V7H001	BOESMANS	ESTCOURT	1928 09 01	1965 03 31	NATAL

Table 2.1: *A breakdown of the first compound gauging weirs constructed in each original province of South Africa.*

Almost without exception all the gauging weirs built in South African rivers until the mid 70's were compound sharp-crested structures. The first compound Crump weir was built in the Great Fish river and started to operate in October 1977.

From information available in DWAF, **Figure 2.1** was compiled to show the growth in the number of flow gauging stations in South African rivers, since 1895. Flow gauging stations were defined as per the following example:

> "At a particular gauging weir a farmer diverts water into two canals to irrigate his lands. The water level is recorded upstream of the weir to determine discharge over the crest of the weir. In the canals flow is gauged with Parshall flumes some distance from the weir. The total discharge available in the river at this station is the flow over the weir plus the flow in the two canals. Although flow is gauged at three separate points, these points together act as one flow gauging station in the river."

The influence of both world wars on the growth of the gauging network is clear from **Figure 2.1**. After World War II the number of operational flow gauging stations grew rapidly until the early 70's. Due to a near optimal number of gauging stations across the country, the start of a network planning program and financial stringency, the number of operational flow gauging stations remained between 800 and 900 since the beginning of 1975. By the end of March 1995 flow was gauged at 818 different stations in South African rivers. Of these stations approximately 55% include components at which flows are gauged with compound sharp-crested weirs and 25% with compound Crump weirs. Flow records at these gauging stations are compiled from roughly 2650 continuous measurements of stage, gate openings and flow meter readings.

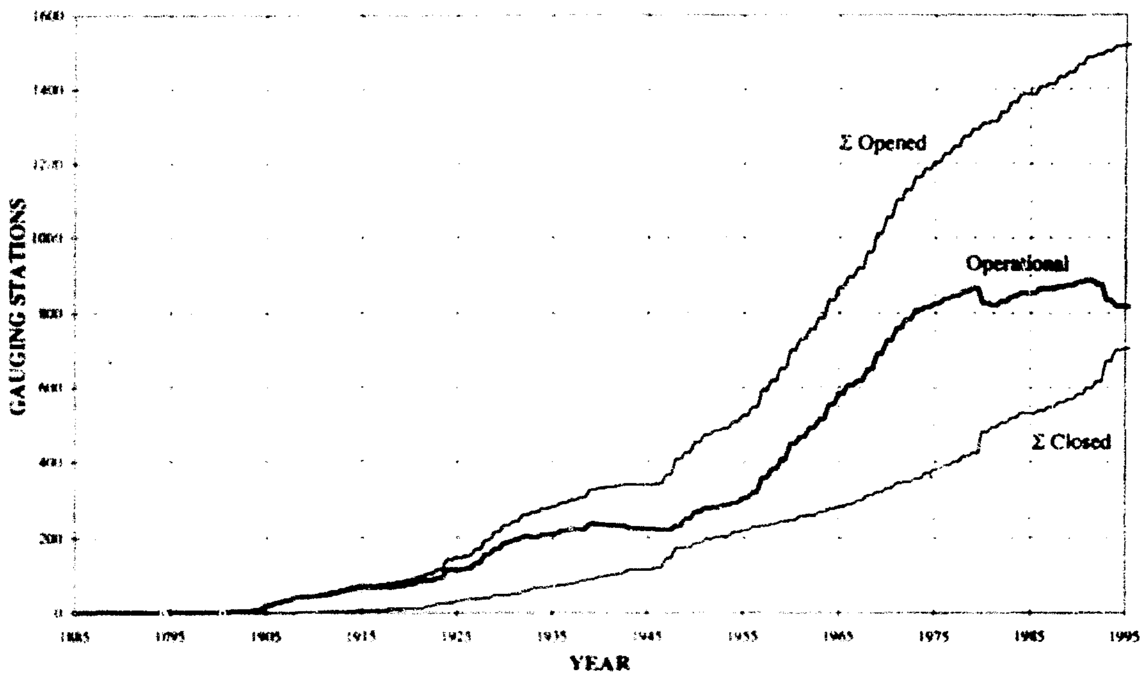


Figure 2.1: *Growth of the flow gauging network in South Africa since 1895.*

Velocity-area rating methods have been used to confirm theoretical calibrations of gauging weirs and to extend the measuring range of these weirs beyond the limit of theoretical calibrations. Sections, rated by velocity-area methods, have not been used extensively for the following practical reasons:

- Vast distances to the respective sites and generally short runoff periods make it logistically difficult to fully rate sections within acceptable time limits,
- a lack of real-time rainfall and runoff data adversely affects reaction times to undertake the necessary gaugings,
- high rainfall making access to sites hazardous and
- a lack of skilled manpower to undertake the required velocity-area gaugings.

The resulting prevalence of compound Crump and sharp-crested weirs amongst South African flow gauging stations indicates that improvements in the calibration theory of these two types of gauging structure would yield the greatest benefits in terms of more accurate flow records.

3. THE IMPORTANCE OF ACCURATE AND RELIABLE FLOW RECORDS.

Gathering of a flow record is a complex, multi-faceted process. To ensure reliability, all the individual steps in the process should be carried out as accurately as possible, within acceptable financial constraints. Simply put, collection costs should not exceed the potential benefit value of a record. Assessment of the collection costs is a relatively simple task; however, determination of the financial benefits is complicated by the following factors:

- It is impossible to identify all the current and future users of flow data,
- difficulty in defining all the benefits that may arise from a flow record and
- benefits from the data are shared by a number of users.

Due to the difficulty in deriving a true cost-benefit relationship for a flow record, it was decided to use more simplified methods to determine the value of accurate and reliable flow records.

Errors in compiling flow records arise in two broad processes:

- collecting and processing of the stage-time record and
- establishment of the unique relationship between stage and discharge.

The potential magnitude of these errors provides an indication of the expected accuracy of a flow record.

3.1 AN INVESTIGATION INTO THE POTENTIAL ERRORS IN THE GATHERING, PROCESSING AND COMPILATION OF A FLOW RECORD.

The establishment of a gauging station is just the beginning of the long and costly process to produce a flow record. As most of the flows in this country are measured by means of gauging weirs the process of producing a flow record from a gauging weir is analysed.

Construction of a gauging weir establishes an artificial control ideally creating a unique relationship between discharge and stage at that point. Once a control has been established two actions are required to determine a flow record; measurement of stage and the derivation of discharge from the stage record.

In South Africa, flow records obtained from gauging weirs are generally gathered, processed and compiled in the following manner:

- The final reading on the stage chart produced by the mechanical recorder is compared to the actual stage reading observed on the gauge plates in the river. The gauge plate reading is taken as correct and adjustments are made to the recorder if necessary, when removing the chart.

- If errors in the automatic stage measurements are discovered, the chart is edited accordingly. This stage-time data is digitised and stored in a database.

- Theoretical calibrations of the weir are used to convert the stage record into a flow record.

Regular inspections of the gauging weirs help to maintain the quality of the stage record. If necessary, debris that may influence the water level, is removed from the weir crest. If there is any indication that the inlet system to the recorder is blocked, the system is flushed to remove the blockage. The partial blocking of the inlet system to the recorder, due to the infiltration of sediment, is probably the most serious problem experienced currently with the recording of stage. A partially blocked inlet system causes the recording of false water levels and the result is a poor and often useless stage record. Errors of this nature are difficult to quantify because of their variable nature; however, regular inspections and corrective actions will minimise their effect.

Although various factors may influence the accuracy of the stage record, human error (including; incorrect gauge readings, pen settings or digitising errors) is one of the main causes for uncertainty in a record. The total uncertainty in the measurement of stage with a mechanical recorder system may be set at roughly ±18 mm (Ackers, 1978; Muller, 1977). This error represents the total inaccuracy due to uncertainties in the gauge zero, gauge plate readings, graph processing and mechanical recorders. The influence of this uncertainty in stage measurement on the accuracy of flow gauging with a horizontal Crump weir of unit crest length and pool depth, is shown in **Table 3.1**.

ACTUAL STAGE (m)	ACTUAL DISCHARGE Q ($m^3/s.m$)	% ERROR IN DISCHARGE
0.10	0.063	+28.3
0.20	0.179	+13.9
0.30	0.331	+ 9.3
0.40	0.514	+ 7.0
0.50	0.726	+ 5.6
0.75	1.368	+ 3.8
1.00	2.162	+ 2.9

Table 3.1: *The influence of an 18 mm overestimation in stage measurements on discharge calculations per unit crest length.*

Factors affecting the proper derivation of discharge from a stage record at a gauging weir are:

- Variations in the pool depth upstream of a weir. Regular surveys of the pool are required to determine whether changes in pool depth are sufficient to influence the theoretical rating of a weir.

- With increasing discharge or variations in river conditions downstream of the weir, non-modular (submerged) flow conditions may develop.

- Accuracy of the calibration theory.

Taking a Crump weir of unit width and pool depth operating under modular flow conditions with a constant stage reading of 1m, **Table 3.2** reflects the potential influence of submergence and upstream pool depth on discharge calculations.

Due to the large contribution of human error in the gathering and processing of a stage record it is difficult to minimise its influence in a flow record. Greater accuracy in calibration theory is therefore a more realistic approach to improve the quality of a flow record in general. Justification for the improvement of flow records can only be based on an assessment of the potential impact of errors in a flow record.

POOL DEPTH (m)	Q ($m^3/s.m$)	% ERROR IN FLOW	% SUBMERGENCE	Q ($m^3/s.m$)	% ERROR IN FLOW
1,00	2,162	0,0	0	2,162	0,0
0,80	2,216	+2,5	75	2,162	0,0
0,60	2,305	+6,6	80	2,101	-2,8
0,50	2,373	+9,8	85	2,050	-5,2
0,40	2,473	+14,2	90	1,958	-9,4
0,30	2,637	+22,0	95	1,450	-32,9

Table 3.2: *Influence of pool depth variations and submergence on discharge calculations for a Crump weir of unit crest length.*

3.2 THE IMPACT OF ERRORS IN A FLOW RECORD ON THE SIZING OF A RESERVOIR.

One of the most important fields of application of flow data is the sizing of reservoirs. Determination of the capacity of a reservoir is dependant on the following factors:

- Flow record at the proposed site.
- Required yield.
- Physical dimensions of the proposed reservoir site, e.g. stage-capacity relationship.
- Evaporation and rainfall effects on the water surface.

If the evaporation and rainfall data is excluded from the analysis (gross yield analysis) then the calculated required capacity is not dependent on location. By using a flow record, with and without errors, to calculate the required reservoir capacity to meet a certain yield, the impact of errors becomes evident. This method provides an indication of the required accuracy for a specific flow record being analysed. To provide a general indicator of the required accuracy for any flow record, in respect of reservoir capacity determination, a number of records should be analysed in this manner.

Selected flow records at 45 different locations spread across the country, as shown in **Figure 3.1**, were analysed. A requirement for the selection was a minimum uninterrupted flow record length of at least forty years. This condition was set in an attempt to ensure that enough high and low flow sequences were represented in the record. Some flow records therefore had to be extended via a rainfall-runoff model in order to meet this minimum record length requirement. In all cases the mean runoff and the coefficient of variation of the extended records were representative of the long term characteristics gauged at the different stations.

In the analysis, the demands or yields, expressed as ratios of the MAR, were evenly distributed through the year. In all cases the extended records were assumed to be a hundred per cent correct. Based on this assumption, required reservoir capacities to satisfy different yields were determined according to the 45 selected records.

After these initial analyses, the flow records were adjusted in an attempt to determine the effect of the errors on the calculated required reservoir capacities. Only the effect of potential underestimations in a record were analysed. A simple approach to adjust the different flow records was adopted by scaling down the monthly flow volumes and MAR of the assumed accurate records with percentages varying between 10% and 40%. In the adjusted records the coefficients of variation were still the same as that of the original records. The gross yield analysis process was again used to determine reservoir capacities in terms of the MAR, to meet the same yields as used in the original analysis. The results of these analyses are shown in tabular and graphical format in **Appendix A** for each gauging station investigated.

The results as shown in **Appendix A** may only be used to determine the impact of underestimation in the record on reservoir capacity for the different stations analysed. This is due to the fact that each individual flow record is only representative of the flows gauged at a particular gauging station. The only way to generalise the results was to determine relative required reservoir capacities needed to satisfy a specified yield. Required reservoir capacities determined for the different yields from the assumed hundred per cent accurate flow records establish the base capacities in this analysis. In this way the impact of incorrect flow gauging on required reservoir capacities are expressed as dimensionless proportions.

Relative required capacities to meet different yields were determined for all 45 gauging stations. The mean value and standard deviation of the relative required reservoir capacities were calculated separately for the different yields. These results are shown in both tabular and graphical format in **Figure 3.2** to **Figure 3.8**. Each of these figures reflects the relative impact of systematic incorrect flow gauging on the required capacity of a reservoir to meet a certain yield, expressed as a percentage of the MAR in a stream. With the help of these figures it is possible to determine the impact of incorrect flow gauging on the required size of a new reservoir. From **Figure 3.5** an underestimation of 10 per cent in gauged flows leads to, on average, a 15 per cent increase in reservoir capacity to meet a yield of 50 per cent of the MAR. Clearly the underestimation of flows result in the development of unnecessarily large reservoirs leading to ineffective capital expenditure. Overestimation of flows on the other hand would lead to even more significant losses due to unexpected shortfalls in supply.

As only one application of a flow record has been examined no clear guidelines for the required accuracy of a record can be set. However, **Figures 3.2** to **3.8** show that, on average, an error in a flow record is magnified when translated into a required reservoir capacity. This indicates that the resulting potential savings increase with increasing gauging accuracy. Evaluation of these benefits can be accomplished by converting them into monetary terms.

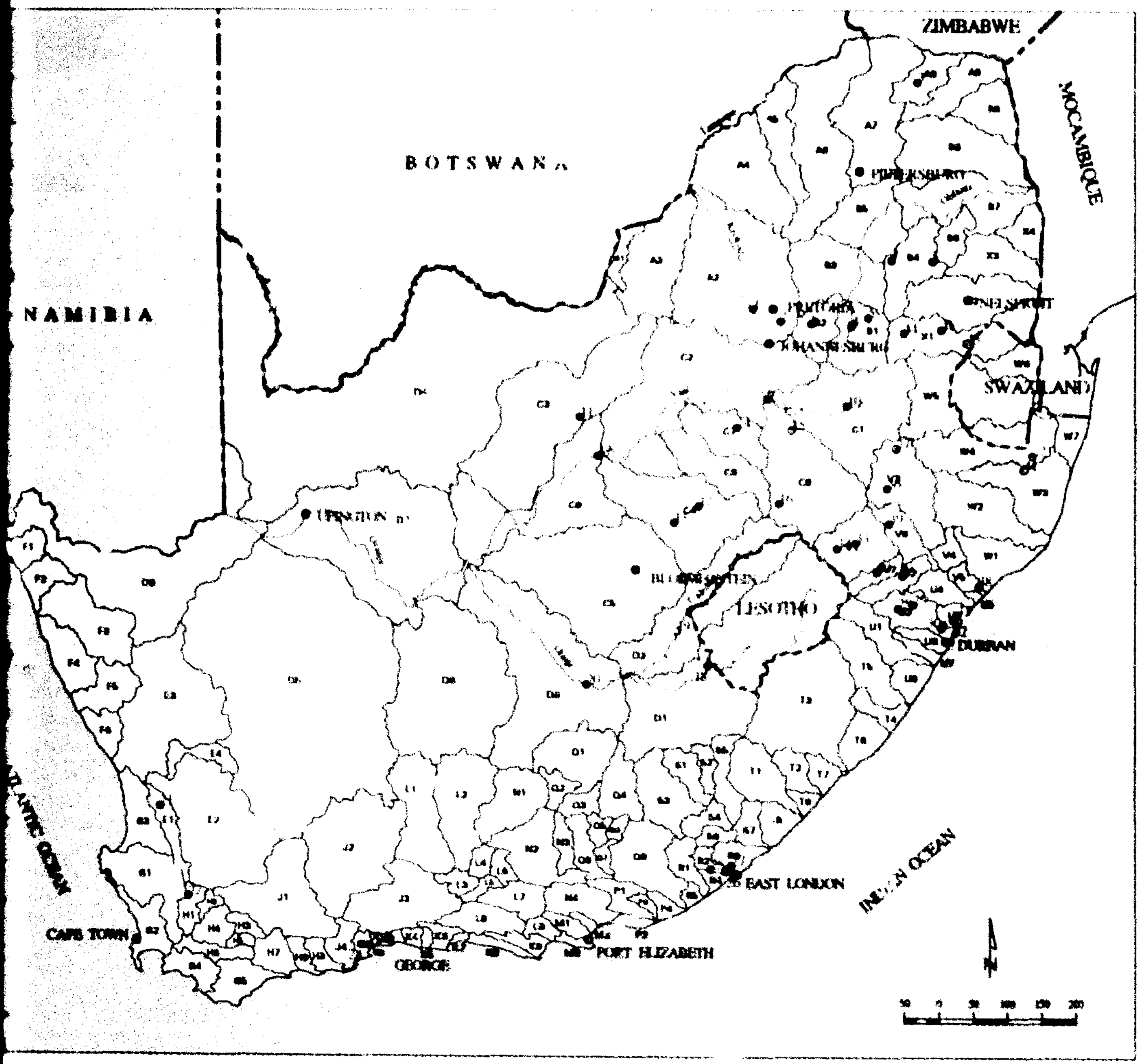


Figure 3.1 :

Localities of Hydrological Gauging Stations Analysed

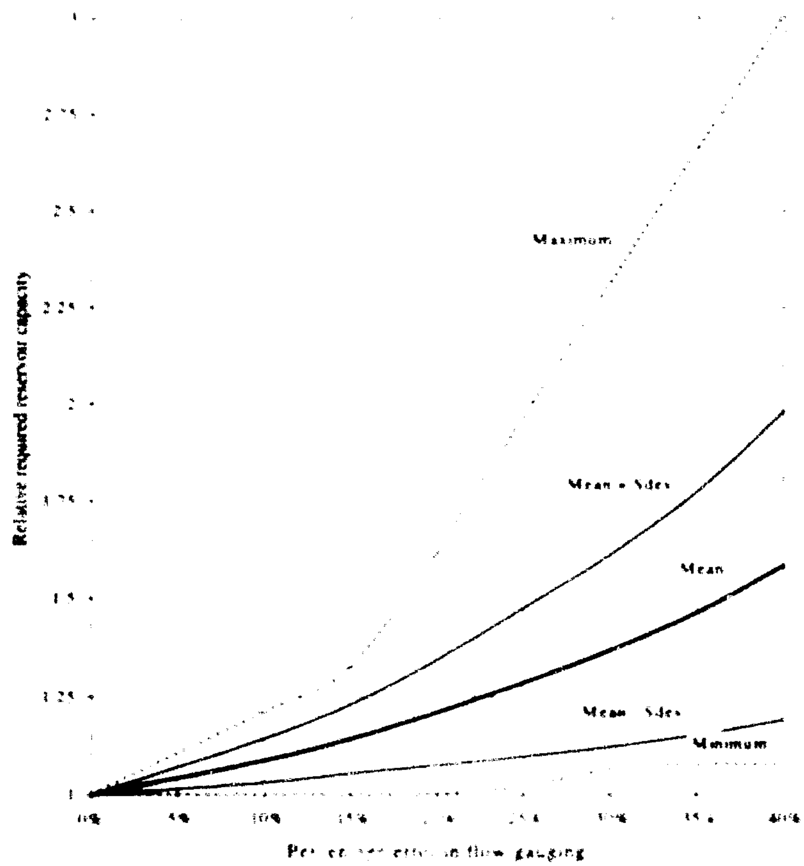
Secondary drainage region

International borders

C3 Secondary drainage region

Gauging Stations

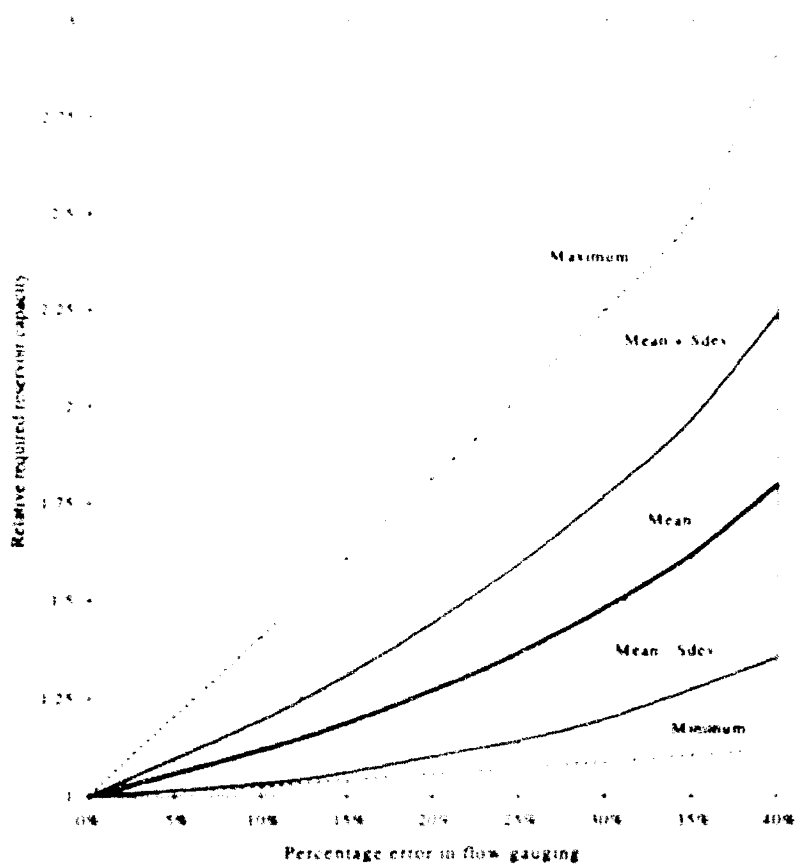
No:	Gauging Station	No:	Gauging Station
1	A2R001	24	K2H002
2	A2R004	25	K2R001
3	[illegible]	26	K2R003
4	B1R001	27	K3R001
5	B1R002	28	U2R001
6	B2R001	29	U2R003
7	B4H003	30	U2R004
8	B4H004	31	U3H001
9	C1R001	32	U3R001
10	C1R002	33	V1R001
11	C3R001	34	V1R003
12	C4R001	35	V2H004
13	C4R002	36	V3R001
14	C7R001	37	V3R003
15	C8H001	38	V5H002
16	C8R004	39	V6H004
17	C9R002	40	V7R001
18	D1H009	41	W3H008
19	D2R004	42	W4R001
20	D3R002	43	X1H001
21	H1R002	44	X1R001
22	H1R003	45	X1R003
23	K1H005		



Error in the gauging of flow as a percentage of the MAR	Relative required reservoir capacity to meet a yield of 20% of the MAR. The required capacity with a 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.09	1.14	1.03	1.21	1.00
-15%	1.14	1.23	1.05	1.32	1.00
-20%	1.21	1.34	1.07	1.62	1.00
-25%	1.28	1.47	1.10	1.96	1.02
-30%	1.37	1.61	1.12	2.31	1.06
-35%	1.46	1.77	1.15	2.66	1.08
-40%	1.58	1.98	1.19	3.01	1.08

Sdev = Standard deviation

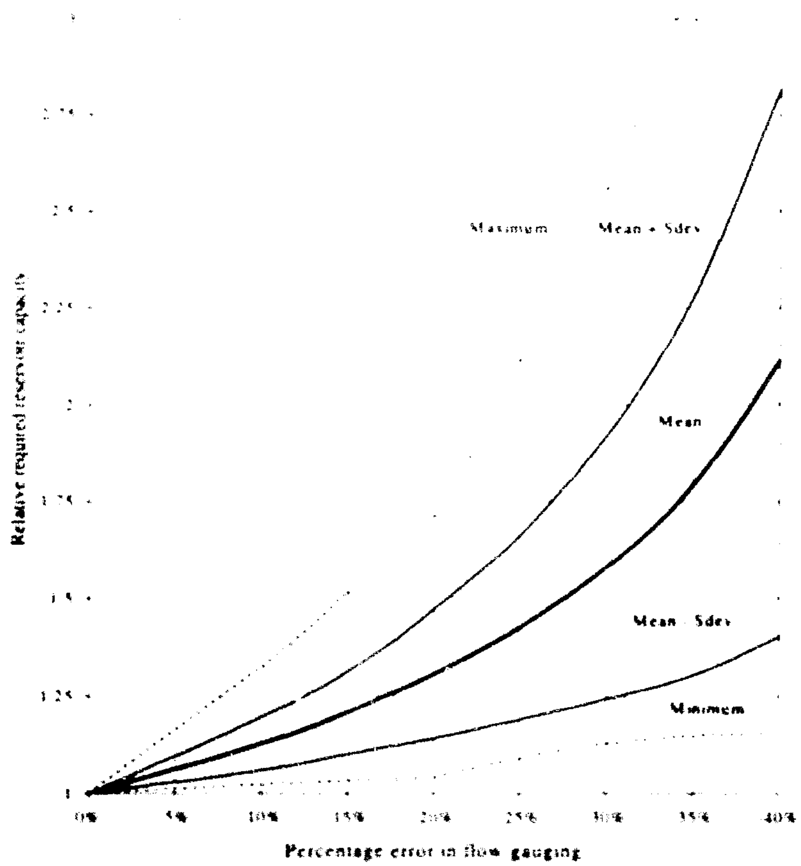
Figure 3.2: *Relative required reservoir capacity to meet a yield of 20% of the MAR.*



Error in the gauging of flow as a percentage of the MAR.	Relative required reservoir capacity to meet a yield of 30% of the MAR. The required capacity with 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.12	1.19	1.03	1.40	1.02
-15%	1.18	1.31	1.06	1.61	1.04
-20%	1.27	1.44	1.10	1.81	1.05
-25%	1.37	1.59	1.14	2.02	1.07
-30%	1.48	1.77	1.19	2.24	1.09
-35%	1.62	1.96	1.27	2.48	1.10
-40%	1.80	2.24	1.35	2.92	1.12

Sdev = Standard deviation

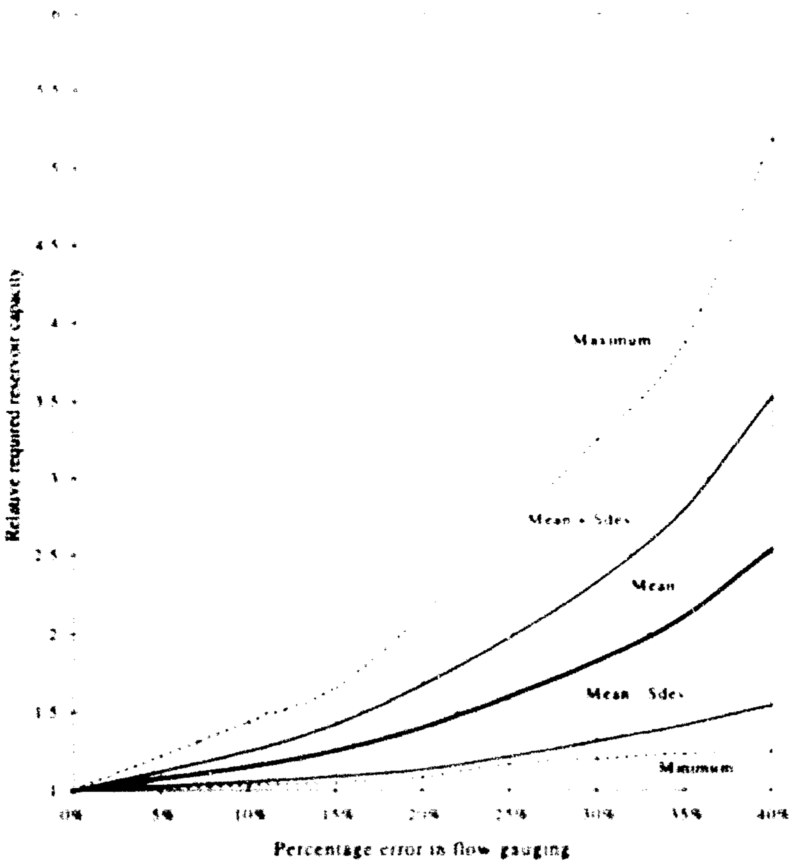
Figure 3.3: *Relative required reservoir capacity to meet a yield of 30% of the MAR.*



Error in the gauging of flow as a percentage of the MAR.	Relative required reservoir capacity to meet a yield of 40% of the MAR. The required capacity with 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.13	1.20	1.06	1.32	1.02
-15%	1.21	1.31	1.10	1.51	1.03
-20%	1.31	1.47	1.14	1.71	1.04
-25%	1.43	1.66	1.19	2.11	1.09
-30%	1.58	1.92	1.24	2.56	1.13
-35%	1.79	2.28	1.30	3.17	1.15
-40%	2.11	2.82	1.40	4.30	1.15

Sdev = Standard deviation

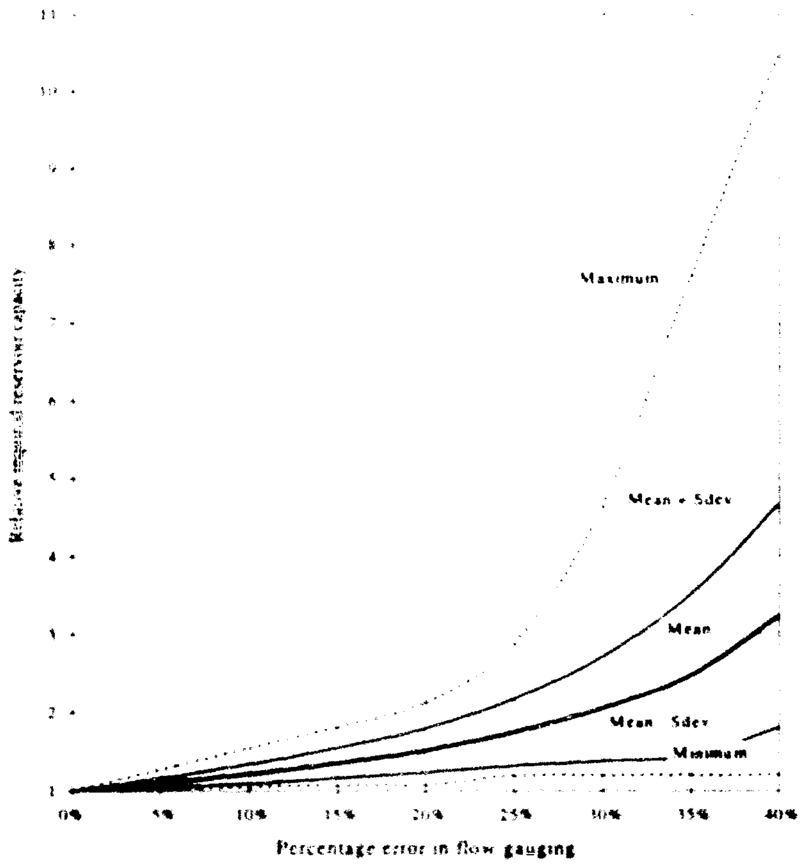
Figure 3.4: *Relative required reservoir capacity to meet a yield of 40% of the MAR.*



Error in the gauging of flow as a percentage of the MAR.	Relative required reservoir capacity to meet a yield of 50% of the MAR. The required capacity with 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.15	1.25	1.06	1.43	1.03
-15%	1.26	1.42	1.09	1.65	1.05
-20%	1.40	1.67	1.14	2.11	1.08
-25%	1.59	1.97	1.22	2.67	1.17
-30%	1.82	2.32	1.32	3.24	1.20
-35%	2.11	2.80	1.42	3.87	1.23
-40%	2.53	3.53	1.54	5.19	1.25

Sdev = Standard deviation

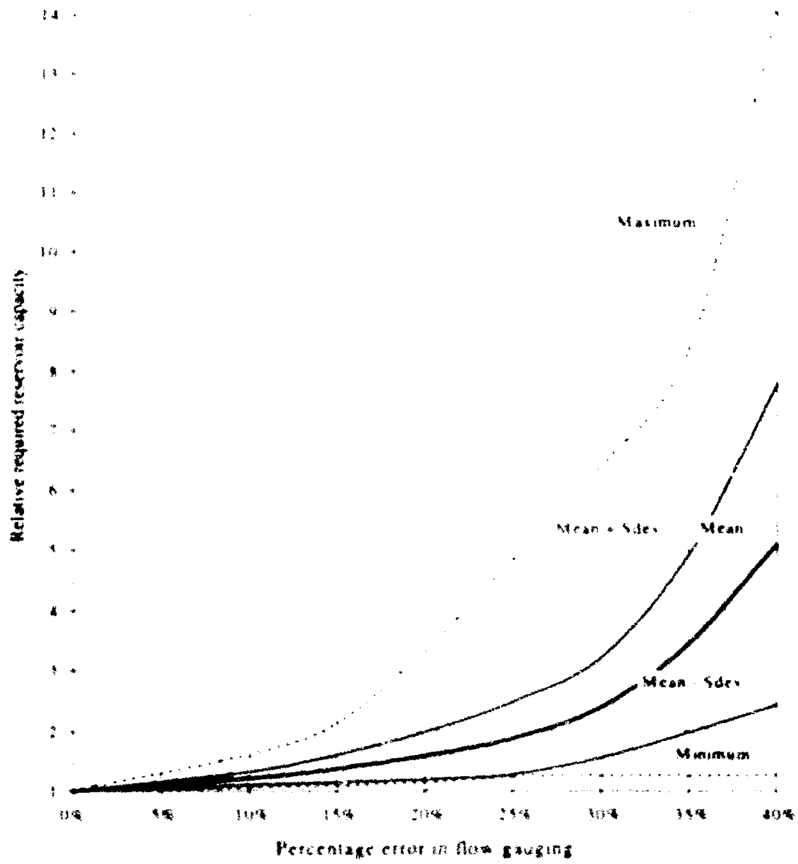
Figure 3.5: *Relative required reservoir capacity to meet a yield of 50% of the MAR.*



Error in the gauging of flow as a percentage of the MAR.	Relative required reservoir capacity to meet a yield of 60% of the MAR. The required capacity with 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.22	1.34	1.10	1.54	1.05
-15%	1.36	1.55	1.17	1.80	1.08
-20%	1.52	1.79	1.24	2.11	1.08
-25%	1.75	2.17	1.32	2.86	1.19
-30%	2.05	2.72	1.38	4.62	1.20
-35%	2.48	3.50	1.45	7.58	1.20
-40%	3.23	4.67	1.80	10.5	1.20

Sdev = Standard deviation

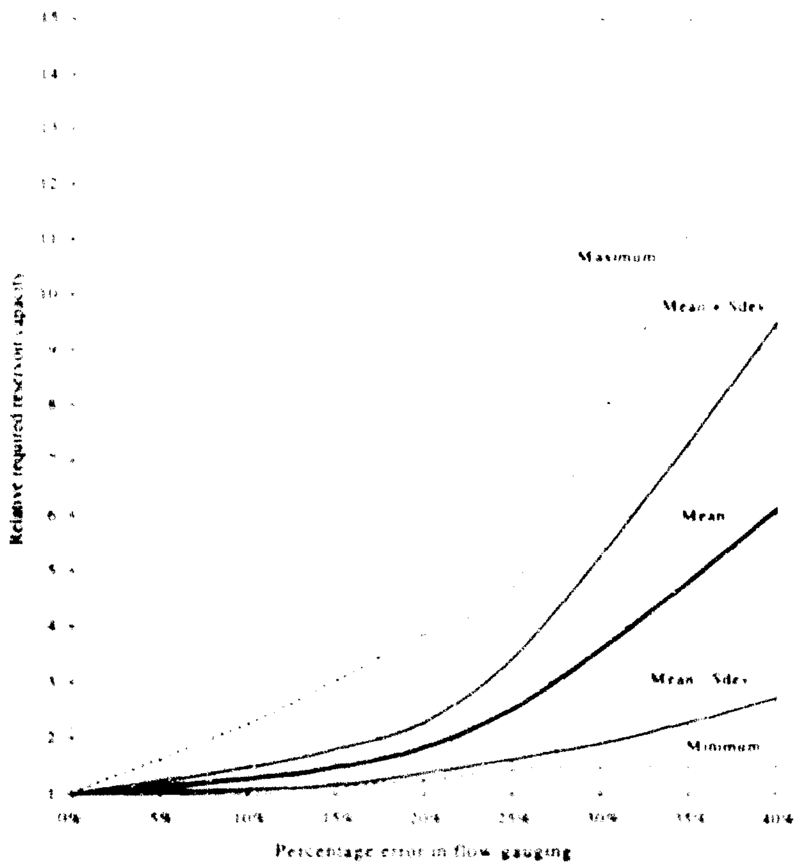
Figure 3.6: *Relative required reservoir capacity to meet a yield of 60% of the MAR.*



Error in the gauging of flow as a percentage of the MAR.	Relative required reservoir capacity to meet a yield of 70% of the MAR. The required capacity with 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.22	1.33	1.10	1.61	1.06
-15%	1.38	1.61	1.15	2.12	1.09
-20%	1.60	1.99	1.20	3.30	1.13
-25%	1.88	2.47	1.29	4.83	1.24
-30%	2.38	3.21	1.56	6.36	1.26
-35%	3.44	4.91	1.97	8.30	1.26
-40%	5.09	7.75	2.42	14.0	1.26

Sdev = Standard deviation

Figure 3.7: *Relative required reservoir capacity to meet a yield of 70% of the MAR.*



Error in the gauging of flow as a percentage of the MAR.	Relative required reservoir capacity to meet a yield of 80% of the MAR. The required capacity with 0% error in the gauging of flow establishes the base capacity used in this analysis.				
	Mean capacity	Mean + Sdev	Mean - Sdev	Maximum	Minimum
0%	1.00	1.00	1.00	1.00	1.00
-10%	1.27	1.46	1.08	2.22	1.05
-15%	1.47	1.79	1.15	3.03	1.15
-20%	1.82	2.27	1.36	3.83	1.23
-25%	2.51	3.41	1.61	4.69	1.41
-30%	3.57	5.26	1.89	7.73	1.47
-35%	4.80	7.32	2.28	11.1	1.47
-40%	6.10	9.48	2.71	14.6	1.47

Sdev = Standard deviation

Figure 3.8: *Relative required reservoir capacity to meet a yield of 80% of the MAR.*

3.3. THE FINANCIAL VALUE OF RELIABLE HYDROLOGICAL DATA.

In an attempt to determine the financial benefits of reliable hydrological data in the sizing of a dam, the flow record used for Wolwedans Dam was analysed. Wolwedans Dam was selected because of the availability of recent and comprehensive financial data on the construction work. Construction of the 70m high dam, built mainly to supply water to the Mossgas project near Mossel Bay, was completed during 1990. On completion the total construction cost of the Wolwedans Dam project, excluding the delivery pipeline to Mossgas, was approximately R 43 000 000 (DWAF, 1993). With the construction of a dam the cost of certain items is almost constant, irrespective of the actual size of the dam. The construction of workforce accommodation, site office, workshops, access roads, security fencing, river diversion, and rehabilitation after completion of the works, are examples of these costs. At Wolwedans Dam the construction cost of items sensitive to the variation in the required storage capacity of the dam was approximately R 32 800 000. This amount divided by the volume of concrete used to construct the dam wall yields a unit price for placed concrete, a figure likely to remain constant within reasonable deviations in dam size.

Assuming the original extended flow record to be correct, the potential yield of the dam was calculated on the basis of the as built capacity of the dam, with a net yield analysis. A net yield analysis, in contrast to a gross yield analysis, considers the influence of rainfall and evaporation on the water surface area of a reservoir. If a record had been collected which underestimated the available flow, an unnecessarily large capacity dam would have been constructed to provide the required yield. From the net capacity versus stage tables for Wolwedans Dam new full supply levels for the dam were determined for various assumed underestimations in gauged flow. The additional capital expenditure of these increased storage capacities were derived from the unit price for placed concrete. Conversely, a record which overestimated the amount of available water would have resulted in too small a reservoir being constructed. In this case the reservoir would not be able to meet the actual demand; either the dam would have to be raised or production by the end user would be affected. **Figure 3.9** shows the impact on capitalisation costs for various assumed flow record inaccuracies.

From **Figure 3.9** an R 11 800 000 overcapitalisation would occur if flows were underestimated by 10 per cent. Overestimation of available flows by 10 per cent and the resulting undercapitalisation in the initial reservoir size would have amounted to R 5 000 000. Since, overcapitalisation is more expensive than undercapitalisation for a specific gauging error because of the dam site features, this results in the two different slopes in the figure.

The potential savings in construction cost that may be achieved with the use of a reliable flow record, as shown in **Figure 3.9** for Wolwedans Dam, represents the direct financial benefit of accurate flow gauging. The prevention of potential financial losses that consumers may suffer due to failures in the supply of water may be described as the indirect financial benefits of a reliable flow record. Difficulties in the determination of these benefits makes their translation into financial terms complex and should be the subject of further research.

In summary, the aim of flow gauging should be to provide the highest possible quality of data, within given financial constraints. This aim can only be reached by maximising the calibration accuracy to rate gauging weirs and minimising human error.

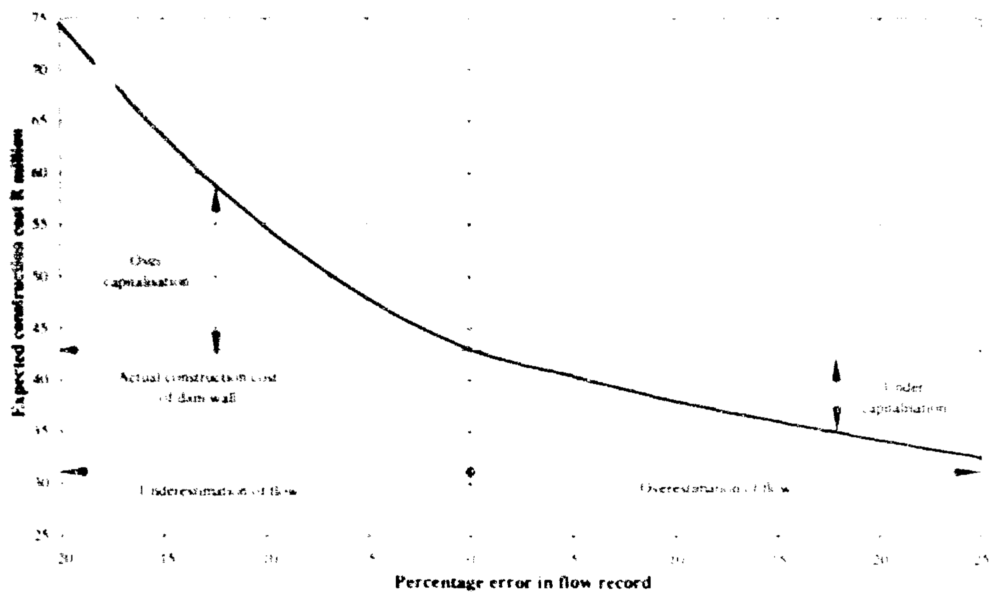


Figure 3.9: *Potential influence of inaccurate hydrological data on the construction costs of Wolwedans Dam.*

4. SHARP-CRESTED AND CRUMP GAUGING WEIRS IN SOUTH AFRICAN RIVERS.

4.1 INTRODUCTION.

Due to the vastness of the country and the related logistical problems it has been the policy of DWAF to establish a gauging network that mainly uses weirs to gauge flows in rivers. Although gauging weirs are relatively expensive structures to build and maintain, their biggest advantage is the creation of a stable artificial control with a known relationship between stage and discharge. A gauging station consists of the approach channel, the downstream channel, the gauging weir and the stage recording instrumentation.

Flow conditions upstream and downstream of a gauging weir are very important as they may influence the accuracy of gauging. The upstream channel should be straight and reasonably regular in cross section for a distance of at least five times the width of the river. This is necessary to ensure that uniform flow conditions exist upstream of the structure. The Froude number (Fr) in the approach channel upstream of the weir should always be less than 0,4 to prevent the formation of unstable flow conditions (Van Heerden, et al., 1986). A deep pool relative to the overflow depth, upstream of a weir, helps to smoothen the water surface and increases the gauging accuracy.

It is important to ensure that a gauging weir is constructed perpendicular to the flow direction in a stream. The structure should also be founded on a good solid foundation and it is essential for the structure to be watertight. The surface of the structure should be smooth, especially in the vicinity of the crest of a weir. Flank walls should be parallel, to the flow direction, as well as being vertical and should extend past the stage measuring position upstream of the structure.

Conditions in the river channel downstream of a weir control the water levels in the river downstream of the structure for different discharges. These levels are of vital importance to optimise the crest level of a gauging weir. It is therefore important to survey the downstream channel of the river prior to the design of a gauging weir and to determine the variation in the downstream water levels with changing discharge.

Sharp-crested weirs were the first type of hydraulic structures to be constructed in South Africa for the gauging of flows in rivers. The first sharp-crested gauging weirs were completed in 1904, whilst the first Crump weir in the country was only constructed during 1977. Nearly all the Crump and sharp-crested weirs in South African rivers are compound gauging weirs.

4.2 COMPOUND GAUGING WEIRS IN SOUTH AFRICA.

South African rivers are subject to large variations in discharge. Compound gauging weirs, composed of a series of weir crests at varying levels, are mostly used to improve the gauging sensitivity during low flows. Low flow in a stream passes only over the lowest crest, or notch, of the weir. As the flow rate increases more of the higher crests start to function. This ensures that discharge can be gauged accurately over a wide range of flow rates without causing an excessive increase in the water level upstream of a weir.

Calibration theory to rate weirs with only a single crest level is well established (Ackers, et al, 1978). To apply this theory to compound weirs each crest should operate as a simple weir without influence from adjacent crest sections. To minimise this interaction, dividing walls should be constructed between the different crest sections, with the difference in adjacent crest levels being restricted to 0,5 m (BSI, 1981). These dividing walls should extend upstream past the section where the head is recorded. The walls should also be high enough to separate the flow throughout the design range of the weir. Furthermore, the British Standards Institution requires a minimum thickness of 0,3 m for dividing walls to avoid sharp curvatures at the entrances, which may be semi-circular or semi-elliptical.

A series of individual weirs operating in parallel is created across the river in this way. Discharge over the individual crests can be rated with the established discharge formulae for a single crest weir if stage is recorded between the dividing walls upstream of each weir section. With a compound weir it is usually not economical to measure water levels upstream of each individual weir section. If water levels are measured only at a single section of a compound weir the total head is assumed constant over the full width of the weir. The total head is calculated at the individual weir section where the water level is recorded.

According to the British Standards Institution (BSI, 1981) compound gauging weirs without dividing walls require in situ or model calibrations. Compound gauging weirs without dividing walls are also not covered by the Standard. From a South African perspective this is probably the most important point in the Standard. More than 95 per cent of all the compound gauging weirs constructed in South Africa to date do not have dividing walls. This was done not only for economic reasons, but also to reduce the risk of floating debris being trapped. Branches and trees entangled by dividing walls adversely affect the accuracy with which flows are gauged. Only a few of these compound structures have been calibrated with in situ flow measurements using current meters.

As mentioned previously, in addition to the omission of dividing walls, it is common practice to record upstream water levels only upstream of the crest with the lowest level. In South Africa it is general practice to measure the head at a distance of four times the design head (H_{max}) upstream of the weir for both sharp-crested and Crump weirs, regardless of whether the weir is equipped with dividing walls or not. All these deviations raised doubts about the gauging accuracy that can be achieved with compound weirs in South Africa.

A clear need for a more systematic and accurate approach to calibrate compound weirs without dividing walls was identified by DWAF. The best way to address this need was to build hydraulic models where discharges could be adjusted and measured accurately while the geometry of the weirs and pools could be varied in a systematic manner. If each weir configuration were tested with and without dividing walls the affect of dividing walls could also be established.

A brief discussion of sharp-crested and Crump weirs follows.

4.3 SHARP-CRESTED WEIRS.

A thin-plate weir has a crest profile consisting of a narrow horizontal top surface at a right angle to the upstream face of a steel plate and a chamfer of not less than 45° on the downstream edge, as shown in **Figure 4.1**. Thin-plate weirs are widely used to gauge flows in hydraulic laboratories. Extensive hydraulic model tests have been performed world-wide on thin-plate weirs to establish formulae to rate this type of structure under a wide variety of flow conditions (Ackers, et al., 1978).

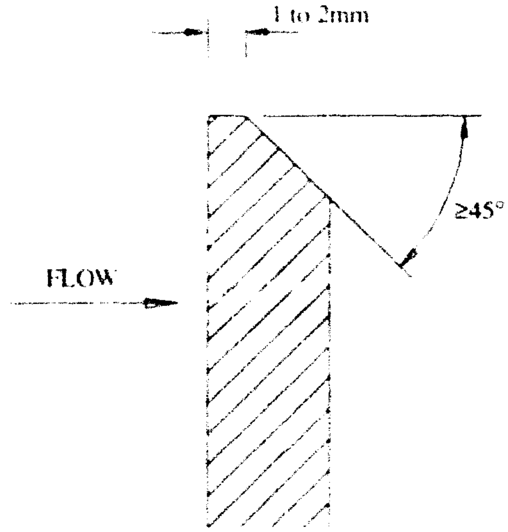


Figure 4.1: *Cross-section through a thin-plate weir.*

The crests of thin-plate weirs are rather fragile and are therefore easily damaged by debris in natural streams. Due to this reason thin-plate weirs are only used on a very limited scale in natural streams. In South Africa the shape of the thin-plate weir was altered to form a sharp-crested weir as shown in **Figure 4.2**.

By using an angle iron to form the crest of the sharp-crested weir, the structure is much more robust than the classical thin-plate weir and is more suitable for use in natural streams and rivers. Nearly all the crest profiles of sharp-crested weirs in South African rivers are built as shown in **Figure 4.2**. The calibration formula to rate thin-plate weirs was adjusted to allow for the use of angle iron crests (Kriel, 1963)

The greatest disadvantage of the sharp-crested weir is its sensitivity to drowned flow conditions. When the water level downstream of a weir rises above the crest level, it starts to influence the gauged head upstream of the weir. This may adversely effect the accuracy of flow measurements with sharp-crested weirs, especially if no corrections are made in the ratings of the gauging structures.

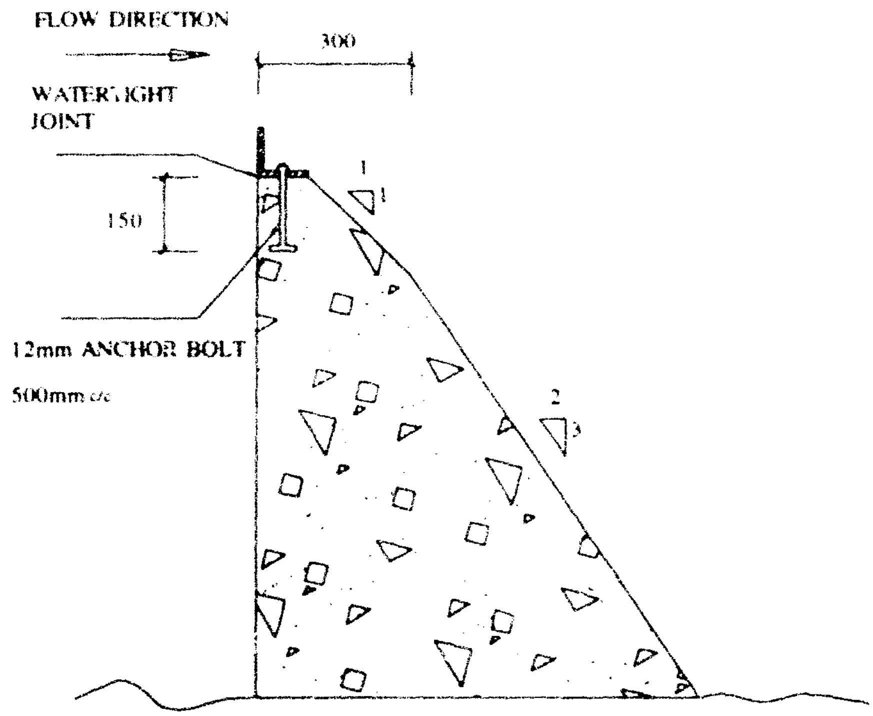


Figure 4.2: *Cross-section through a sharp-crested weir.*

A discussion on the theory to rate a sharp-crested weir follows at a later stage.

4.4 CRUMP WEIRS.

The Crump weir is at present the most popular type of triangular weir world-wide. E.S. Crump published a paper during 1952 in England in which he described a new type of triangular profile weir. Upstream and downstream slopes of this triangular profile weir are 1:2 and 1:5 respectively. There are two types of Crump weirs used for flow measurement in natural streams, namely the horizontal Crump weir, see **Figure 4.3**, and the V-form Crump weir. In South Africa the side slopes of the V-Crump are presently standardised at 1 vertical to 10 horizontal, as shown in **Figure 4.4**. The advantage of the V-Crump's accuracy at low flows can also be achieved by combining (compounding) horizontal Crump crests at different levels in a structure. Therefore, only compound horizontal Crump weirs will be analysed in this document.

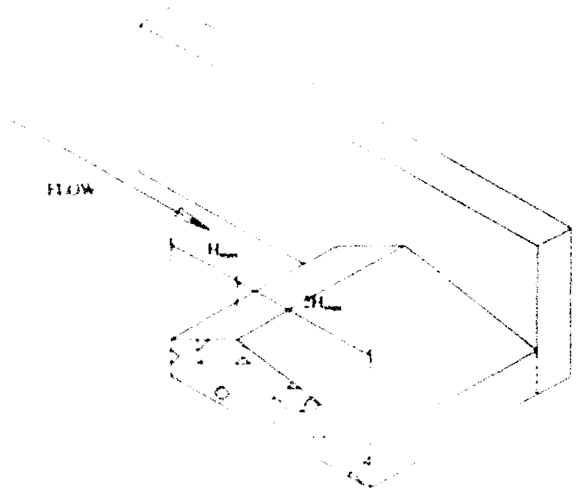


Figure 4.3: *Horizontal Crump structure.*

The Crump weir is relatively easy to construct. It is a robust structure and is insensitive to minor damage to the triangular profile of the crest. The greatest advantages of a Crump weir are a stable and constant coefficient of discharge in the modular flow range and a relative insensitivity of the structure to drowned flow conditions. A discussion of the formulae to rate Crump and sharp-crested weirs follows.

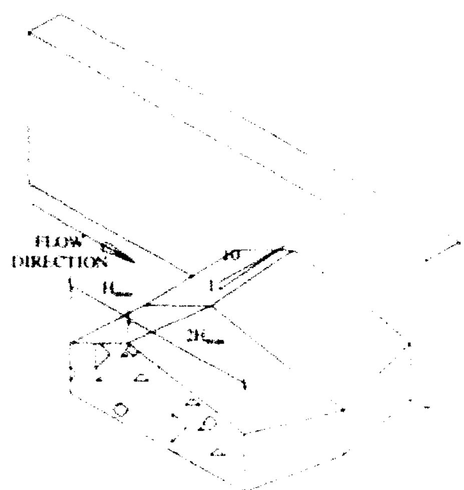


Figure 4.4: *V-Crump structure.*

5 DISCHARGE FORMULAE FOR CRUMP AND SHARP-CRESTED WEIRS.

The basic hydraulic principle mostly applied in flow gauging structures with free surface flows, is to create artificial controls which enforce a transition from subcritical to supercritical flow conditions. Unique relationships are created between the upstream water level and the discharge over the structure. Different approaches are required to derive basic theoretical discharge formulae for Crump and sharp-crested weirs. The triangular profile Crump weir is in principle a long-base weir and the derivation of the basic theory is based on that for a broad-crested weir. In the case of the sharp-crested weir the theory for a thin-plate weir is used.

5.1 FORMULAE TO RATE THE DISCHARGE OVER A CRUMP WEIR.

5.1.1 THE DERIVATION OF THE BASIC DISCHARGE FORMULA FOR A CRUMP WEIR.

Being a long-base weir, the theoretical derivation of a discharge formula for a Crump weir is based on the theory for a broad-crested weir. Assumptions used in the derivation of the discharge formula for a broad-crested weir are as follows:

- Flow in the approach channel upstream of the weir is uniform. Flow lines are parallel, velocities are constant and the pressure variation is hydrostatic.

- The crest of the weir is horizontal and sufficiently long in the direction of flow to ensure that flow lines are parallel to the crest. Hydrostatic pressure variation exists near the downstream end of the weir.

- Critical depth occurs at the control section near the downstream end of the weir. The weir operates under modular flow conditions, that is drowned flow conditions do not occur.

- Effects of viscosity and surface tension are neglected.

- Energy losses between the upstream section and the control section on the weir are negligible.

Applying the Bernoulli equation between sections 1 and 2 in **Figure 5.1** the derivation of the discharge formula is as follows:

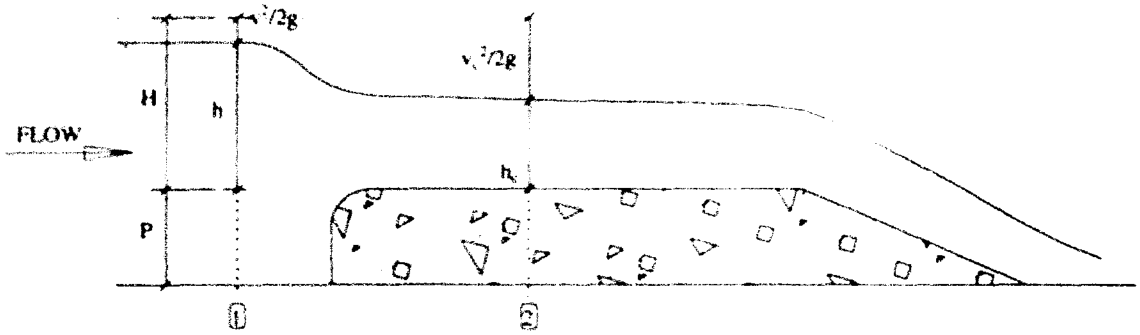


Figure 5.1: *Flow over a broad-crested structure.*

$$h_c + \frac{v_c^2}{2g} = h + \frac{v^2}{2g} = H$$

In a rectangular channel with a width l:

$$h_c = \sqrt[3]{\frac{Q_t^2}{l^2\,g}} \qquad (5.1)$$

where Q_t is the theoretical discharge at the critical section.

$$\text{also } v_c\,h_c = \frac{Q_t}{l}$$

$$\Rightarrow \quad \frac{h_c}{2} = \frac{v_c^2}{2g}$$

$$\therefore h_c = \frac{2}{3}H$$

and substituting in equation (5.1) results in

$$\sqrt[3]{\frac{Q_t^2}{l^2 g}} = \frac{2}{3} H$$

$$\therefore Q_t = \frac{2}{3}\, l \sqrt{\frac{2}{3} g}\; H^{3/2} \tag{5.2}$$

By introducing a discharge coefficient (C_d) to convert the theoretical discharge (Q_t) to a real discharge (Q), equation (5.2) becomes

$$Q = C_d \frac{2}{3}\, l \sqrt{\frac{2}{3} g}\, H^{3/2} \tag{5.3}$$

None of the assumptions made in the derivation is unrealistic provided that the crest of the broad-crested weir is sufficiently wide and that it operates under modular flow conditions. In equation (5.3) the discharge coefficient (C_d) has to compensate mainly for the small energy loss between sections 1 and 2. In the case of the broad-crested weir values of C_d are normally close to unity with $C_d \approx 0{,}98$ a typical value. The influence of contraction losses between sections 1 and 2 plays an insignificant role in the discharge coefficient and therefore C_d is independent of h and P values.

When the broad-crested weir formula, equation (5.3), is applied to the Crump weir the assumption of horizontal and parallel flow over the weir crest is invalid. Flow lines over the control section are now clearly curved and a separation pocket forms just downstream of the crest of the Crump weir as shown in **Figure 5.2**. Pressures at the control section are now lower than hydrostatic and this will therefore influence the value of the discharge coefficient. This has the effect of increasing the discharge coefficient to values higher than that for a classical broad-crested weir and leads to C_d values larger than unity. As is the case with the broad-crested weir, C_d remains constant and is also independent of the gauged head (h) relative to the crest of the weir and the pool depth (P).

Figure 5.2: *Flow lines over a Crump weir.*

5.1.2 CRUMP DISCHARGE FORMULA FOR MODULAR FLOW CONDITIONS.

Discharge over a weir may be classified as modular when it is independent of variations in the water level downstream of the structure. Extensive research to rate Crump weirs has been undertaken in the past. From this research, the discharge formula to rate a Crump weir (BSI, 1986) for modular flow conditions is:

$$Q = C_d \frac{2}{3}\sqrt{\frac{2}{3}g}\; l\, H^{\frac{3}{2}} \qquad (5.4)$$

with $C_d = 1{,}163\left(1 - \frac{0{,}0003}{h}\right)^{\frac{3}{2}}$

The following general limitations delineate the applicability of the formula:

- $h \geq 0{,}06$ m for a crest section of fine concrete or equivalent;
- $P \geq 0{,}06$ m;
- $l \geq 0{,}30$ m;
- $h/P \leq 3{,}5$;
- $l/h \geq 2{,}0$.

Within these limitations the value of C_d can vary between 1,157, if h is equal to 0,06 m, and 1,163 for large values of h. This variation is less than 1% and the value of C_d may be taken at a constant value of 1,163 for practical purposes. The value of C_d is greater than unity due to convex flow lines and the forming of a separation pocket just downstream of the crest of the Crump weir.

5.1.3 DISCHARGE FORMULA TO RATE A CRUMP WEIR FOR DROWNED FLOW CONDITIONS.

In drowned flow conditions the stage-discharge relationship for a Crump weir depends on both the upstream and downstream water levels. Provision was made in the original design of the Crump weir to gauge tailwater levels with a tapping in the downstream face of the weir, close to the crest. In South Africa, problems are experienced with sediment particles blocking the crest-tappings. Water levels recorded downstream of the hydraulic jump are used to correct for the influence of drowned flow conditions.

The discharge formula to rate a Crump weir for drowned flow conditions (Ackers, et al., 1978) is:

$$Q = C_4\, f\, \frac{2}{3}\sqrt{\frac{2}{3}g}\; l H^{3/2} \tag{5.5}$$

where $C_4 = 1{,}163\left(1 - \frac{0{,}0003}{h}\right)^{3/2}$

and

$f = 1.00$ if $0{,}75 \geq {H_2}/{H}$

$f = 1{,}035\left[0{,}817 - \left(\frac{H_2}{H}\right)^4\right]^{0{,}0647}$ if $0{,}75 < {H_2}/{H} \leq 0{,}93$

$f = 8{,}686 - 8{,}403\frac{H_2}{H}$ if $0{,}93 < {H_2}/{H} \leq 0{,}985$

The ratio between the total downstream head (H_2) and the total upstream head (H) indicates the degree of submergence of the weir.

5.2 FORMULAE TO RATE THE DISCHARGE OVER A SHARP-CRESTED WEIR.

5.2.1 DERIVATION OF THE BASIC DISCHARGE FORMULA FOR A SHARP-CRESTED WEIR.

The derivation of a basic discharge formula for the sharp-crested weir, as given below, is based on the derivation for a thin-plate weir (Massey, 1975).

Consider a sharp-edged rectangular weir as shown in **Figure 5.3**.

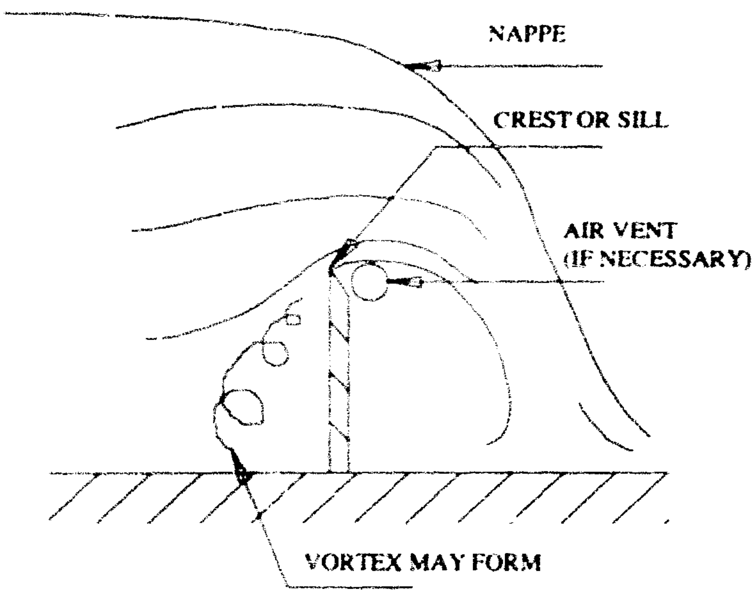


Figure 5.3: *Flow pattern over a thin-plate weir.*

The classical analysis is based on four assumptions:

- Flow conditions in the approach channel upstream of the weir are uniform. Flow lines are therefore parallel, velocities are constant and the pressure variation is hydrostatic.

- The draw-down of the free water surface as the flow approaches the crest of the weir is ignored. That implies that all particles passing over the crest move horizontally.

- Pressure throughout the nappe is atmospheric.
- The effects of viscosity and surface tension are negligible.

Taking these assumptions into account an idealised flow pattern as shown in **Figure 5.4** is obtained.

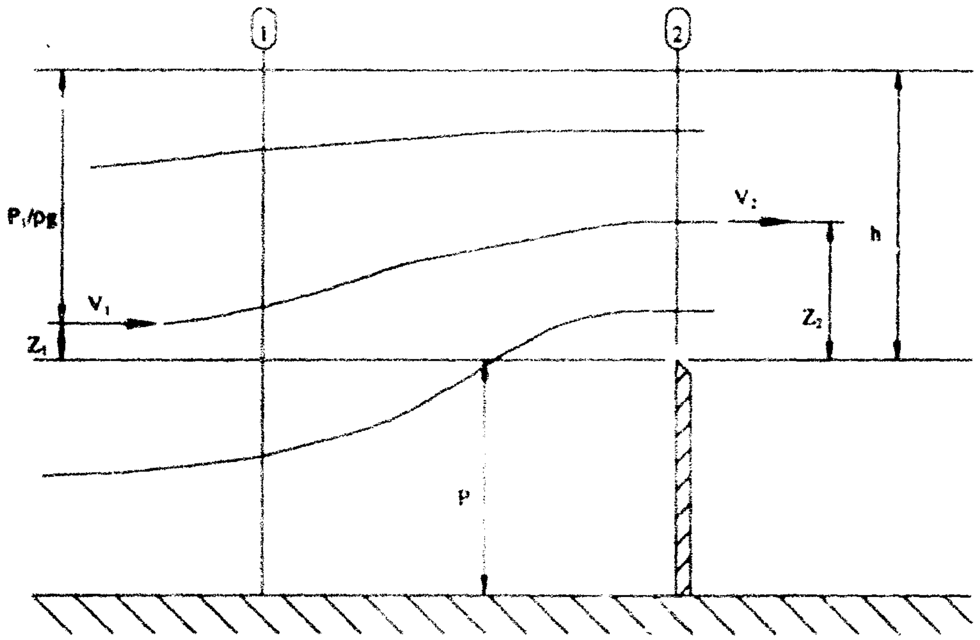


Figure 5.4: *Idealised flow pattern over a thin-plate weir* (Massey, 1975).

If the Bernoulli equation is applied along a streamline in **Figure 5.4**, then:

$$\frac{p_1}{\rho g} + Z_1 + \frac{v_2^2}{2g} = 0 + Z_2 + \frac{v_2^2}{2g}$$

but since $h = Z_1 + \frac{p_1}{\rho g}$ the equation reduces to

$$h + \frac{v_1^2}{2g} = Z_2 + \frac{v_2^2}{2g}$$

and this may be rewritten as

$$v_2 = \left[2g\left(h - Z_2 + \frac{v_1^2}{2g}\right)\right]^{1/2}$$

The theoretical discharge (Q_t) over a weir with a width l, is

$$
\begin{aligned}
Q_t &= l\int_0^{h} v_2 \, dz_2 \\
&= \frac{2}{3}\, l\sqrt{2g}\left[\left(h+\frac{v_1^2}{2g}\right)^{3/2}-\left(\frac{v_1^2}{2g}\right)^{3/2}\right] \qquad (5.6)\\
&= \frac{2}{3}\, l\sqrt{2g}\left[H^{3/2}-\left(\frac{v_1^2}{2g}\right)^{3/2}\right]
\end{aligned}
$$

Thus far, only the assumption that the water surface remains horizontal up to the crest of the weir is highly questionable. The other assumptions are normally not unreasonable provided that

- A deep and regular pool is created upstream of the weir to ensure uniform flow conditions.
- The nappe is properly aerated.
- The depth of the water flowing over the weir is not too small.

Introducing a discharge coefficient (C_d) to equation (5.6) the theoretical or apparent discharge (Q_t) is converted to a true discharge (Q):

$$
Q=C_d\frac{2}{3}\, l\sqrt{2g}\left[H^{3/2}-\left(\frac{v_1^2}{2g}\right)^{3/2}\right] \qquad (5.7)
$$

In contrast to the broad-crested weir, the discharge coefficient (C_d) in equation (5.7) mainly compensates for the contraction losses between sections 1 and 2, and the idealised assumption of ignoring the draw-down of the free water surface near to the weir crest. It can be expected that the discharge coefficient should possess values similar to a contraction coefficient for a rectangular orifice, which are in the order of C_d = 0,6. Because the contraction at the bottom of the nappe will also be dependent on the degree to which the flow is contracted from the pool to the crest of the weir, a dependence can be expected between C_d and h/P.

Discharge over a thin-plate weir can only be determined through an iteration process if equation (5.7) is used. This is necessary since the upstream velocity v_1 depends on the discharge (Q). This equation is frequently simplified by neglecting the last $\left(\frac{v_1^2}{2g}\right)^{3/2}$ term in equation (5.7), which leads to

$$Q = C_d \frac{2}{3} l \sqrt{2g}\, H^{3/2}$$

The discharge formula for a thin-plate weir has found wide acceptance in this more fundamental form, because it expresses the discharge as a function of the total head (H) rather than the water head (h).

5.2.2 FORMULAE TO RATE A SHARP-CRESTED WEIR FOR MODULAR FLOW CONDITIONS.

In the International Organisation for Standardisation document (ISO, 1980) the following discharge formulae are given to rate a thin-plate weir for modular flow conditions; namely:

- Kindsvater-Carter formula (Ackers, et al., 1978)
- SIA formula (Society of Swiss Engineers and Architects) (Ackers, et al., 1978)
- Rehbock formula (Ackers, et al., 1978)
- IMFT formula (Institut de Mecanique des Fluides de Toulouse) (Ackers, et al., 1978)

Uncertainties attributed to the discharge coefficient in these formulae, at the 95% confidence level, is less than 1,5% if h/P is lower than 1,0; less than 2% if h/P is between 1,0 and 1,5 and not greater than 3% if h/P is between 1,5 and 2,5. These accuracies are applicable only if additional restrictions on the values of h, l, P, h/P and $(B-l)/2$ are met (ISO, 1980).

THE IMFT DISCHARGE FORMULA.

Because of the similarity in the calculated discharge values obtained by applying the various formulae, it was decided to investigate the IMFT formula only. The IMFT formula is the only formula that is written directly in terms of the total head H, rather than the overflow depth h. The inclusion of the $v^2/2g$ term leads to a formula with a discharge coefficient that does not vary greatly, since it agrees more closely with the basic theory.

The IMFT formula for a full-width weir is:

$$Q = C_d \frac{2}{3}\sqrt{2g}\, l H^{3/2} \qquad (5.8)$$

with $C_d = 0{,}627 + 0{,}018 \dfrac{H}{P}$

Restrictions on the applicability of the IMFT formula are:

- $h/P < 2{,}5$
- $h > 0{,}03$ m
- $l > 0{,}20$ m
- $P > 0{,}10$ m

The IMFT equation agrees with the form of the basic discharge formula as derived in the previous section. Within the restrictions set above, the value of the discharge coefficient (C_d) in the IMFT equation varies between 0,627 if $H/P = 0$ and 0,679 for $H/P = 2{,}9$; which is a variation of roughly 8%.

THE DWAF DISCHARGE FORMULAE.

Due to the high sediment load of rivers in South Africa, the upstream pools of weirs tend to silt up. This reduces the pool depth (P) upstream of a weir and often creates h/P ratios greater than 2,5. To overcome this problem DWAF initiated research to address this problem and the equations presently in use to rate thin-plate and sharp-crested weirs were developed.

The DWAF equation to rate thin-plate weirs is :

$$Q = 1{,}777\ l\ C_p\ (H + 0{,}001)^{3/2} \qquad (5.9)$$

The coefficient C_P is included in order to cover a wider range of H/P values as set for the formulae in the publication of the International Organisation for Standardisation document (ISO, 1980). Values for the coefficient C_P are as follows:

$$C_p = 1{,}000 + 0{,}11\left(\frac{H}{H+P}\right)^{1{,}24} \qquad \text{if} \qquad H/P \leq 3{,}4$$

$$C_p = 1{,}145\left(\frac{P}{H+P}\right)^{0{,}04} \qquad \text{if} \qquad 3{,}4 < H/P \leq 200$$

$$C_p = 0{,}926 \qquad \text{if} \qquad H/P > 200$$

The DWAF discharge equation (Le Roux, et al., 1990) to rate sharp-crested weirs fitted with angle iron crests is the same as (5.9), but is replaced with (5.10) in the range specified:

$$Q = 1{,}61\ l\ C_p\ (H + 0{,}001)^{1{,}416} \qquad (5.10)$$

only if $H \leq 0{,}310\text{m}$ and $H/P \leq 3{,}40$, C_p values as per (5.9).

Equation (5.10) provides for the influence of the angle iron crest on the discharge over the sharp-crested weir and includes the results of earlier research by Kriel (1963).

Although it is possible to use these equations to rate thin-plate and sharp-crested weirs with a very shallow pool depth (P), caution is advised when the Froude number (Fr) exceeds a value of 0.4 in the approach channel.

The DWAF equations were evaluated (Hydraulics Research, 1986) as part of an assessment study of the potential water yield of the Lesotho Highlands Water Project.

This evaluation revealed an inherent error in the equations of approximately ±2% for values of $H/P < 3.4$ increasing linearly to ±6% when $H/P = 8.0$. In this assessment it was recognised that DWAF equations were designed to cover a wide range of upstream pool depths and describes these flow conditions better than alternative formulae.

5.2.3 DISCHARGE FORMULAE TO RATE THIN-PLATE WEIRS FOR DROWNED FLOW CONDITIONS.

Thin-plate weirs are usually designed to operate only in modular flow conditions. In South Africa sharp-crested weirs are widely used to gauge flow in natural streams. It happens quite often that downstream water levels are higher than the crest elevations of these weirs. In these circumstances the weirs operate under drowned conditions and the ratings of the weirs should be adjusted accordingly. Under drowned flow conditions the discharge over a weir is dependant on both the upstream and downstream water levels. The best known equation to correct for the influence of drowned flow conditions is that of Villemont (1947) and reads as follows for a rectangular thin-plate weir:

$$Q = Q_d\left[1-\left(\frac{h_2}{h}\right)^{3/2}\right]^{0.385} \tag{5.11}$$

where

- Q = The actual discharge in the stream.
- Q_d = Discharge determined as for modular flow conditions for an upstream head (h), as gauged under drowned flow conditions.
- h_2= Downstream water level, relative to crest elevation.

as shown in **Figure 5.5**.

Different equations, including that of Villemont, were used by DWAF to correct for drowned flow conditions at sharp-crested weirs. Vast discrepancies between the results of these equations led to a research project to determine the influence of submergence on discharge. This resulted in a new technique to calculate drowned discharges and is presently used by the Department. With this technique (Wessels, 1986) an equivalent theoretical modular flow condition, with the same discharge, is created for the gauged drowned flow condition at the weir. Once the equivalent modular flow situation is established, discharge can be calculated as if there is no submergence.

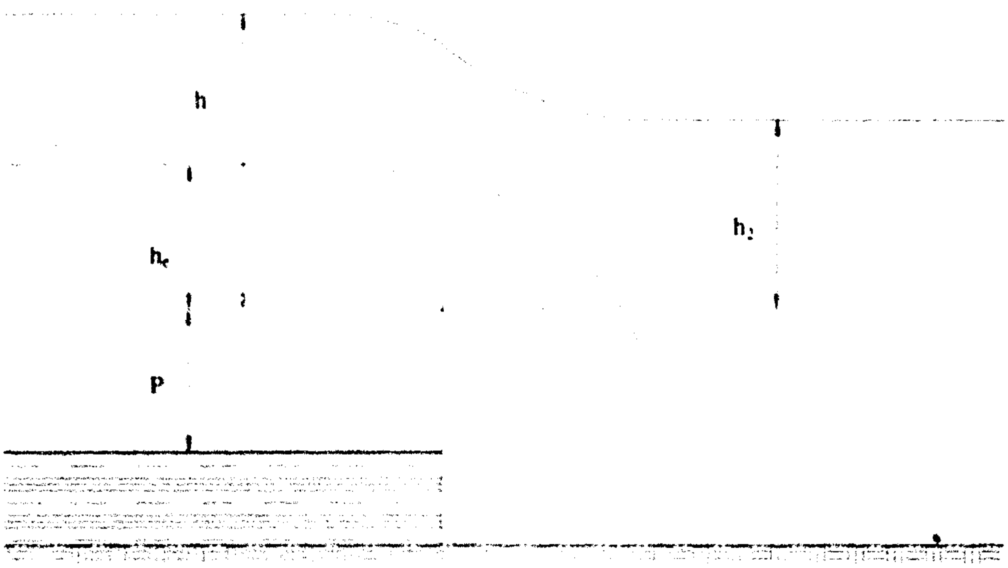


Figure 5.5: *Definition sketch of parameters used in the non-modular flow equations for a thin-plate weir.*

With this method it is possible to determine discharge for submergence in excess of 90%. The equations to create an equivalent modular flow condition are as follows:

$$h_e = \frac{h\sqrt{1-\left(\frac{h_2}{h}\right)^2}}{\alpha} \qquad (5.12)$$

with

$$\alpha = \frac{-b+\sqrt{b^2-4c}}{2}$$

$$b = -0{,}3407 - 0{,}3062\left(\frac{h_2}{h}\right)$$

$$c = 0{,}6288\left(\frac{h_2}{h}\right)^2 + 0{,}1016\left(\frac{h_2}{h}\right) - 0{,}6096$$

where

- h_e = The equivalent modular upstream head;
- h = The gauged upstream head (drowned flow condition);
- h_2 = Downstream gauged head relative to crest.

as shown in **Figure 5.5**.

6. DESCRIPTION OF THE HYDRAULIC MODEL TESTS.

6.1. OBJECTIVES OF THE HYDRAULIC MODEL TESTS.

With compound weirs the flow conditions upstream of the weir are no longer two-dimensional, especially in the case of compound weirs without dividing walls. Some of the assumptions made in the derivation of the basic discharge formulae in **Chapter 5** are violated if flow is gauged with compound weirs. Errors in the gauging of flow are expected to increase in relation to the degree that the assumptions are violated. Parameters causing the highest degree of cross flow will affect the gauging accuracy the most. These parameters are; the difference in adjacent weir crest levels, the relative depth of flow over adjacent crests, the proportional lengths of neighbouring notches and the comparative flow velocities in the pool upstream of each crest. Most of these parameters influence each other and the difference in adjacent crest levels will affect nearly all the other parameters.

A systematic test programme was required to determine the influence of all these parameters on the accuracy of flows gauged with compound weirs. In the tests these parameters were varied to cover conditions that can be expected in reality. To establish the influence of the dividing walls on the accuracy of flow gauging each model configuration was tested with and without walls. All tests were performed under modular flow conditions and the approach channel was rectangular in most of the tests. Some tests were conducted to determine the influence of irregular upstream pool conditions on the accuracy of flows gauged with compound weirs.

6.2 MODEL FACILITIES AND LAY-OUT.

6.2.1 GENERAL.

Tests on compound Crump weirs were undertaken in the hydraulics laboratory of DWAF in Pretoria. Compound Crump and sharp-crested weirs were also tested in the hydraulics laboratory of the Department of Civil Engineering, University of Stellenbosch. These tests were run as part of a project of the Water Research Commission. The maximum error in the discharge gauged at both hydraulic laboratories is estimated to be less than ±1,5% of the actual discharge. A brief description of the facilities and the tests performed at both these institutions follows.

6.2.2 HYDRAULIC MODEL FACILITIES USED IN THE HYDRAULICS LABORATORY OF DWAF.

A schematic layout of the test facility in the hydraulics laboratory of DWAF in Pretoria is shown in **Figure 6.1**. Water was supplied to the model from a constant head tank, about 8m above the model floor, via a 0,3 m diameter delivery pipe. Electromagnetic flow meters were used to measure the flow rate supplied to the model. The maximum discharge through the model was roughly 0,180 m^3/s. Volumetric methods were used to check the accuracy of the electromagnetic flow meters on a regular basis. The water was discharged into the model basin using a diffuser and grid system, to ensure uniform flow conditions with minimum surface disturbance in the approach channel to the weir. In the model the approach channel was approximately 4m wide and 8m long and also formed the upstream pool of the weirs tested.

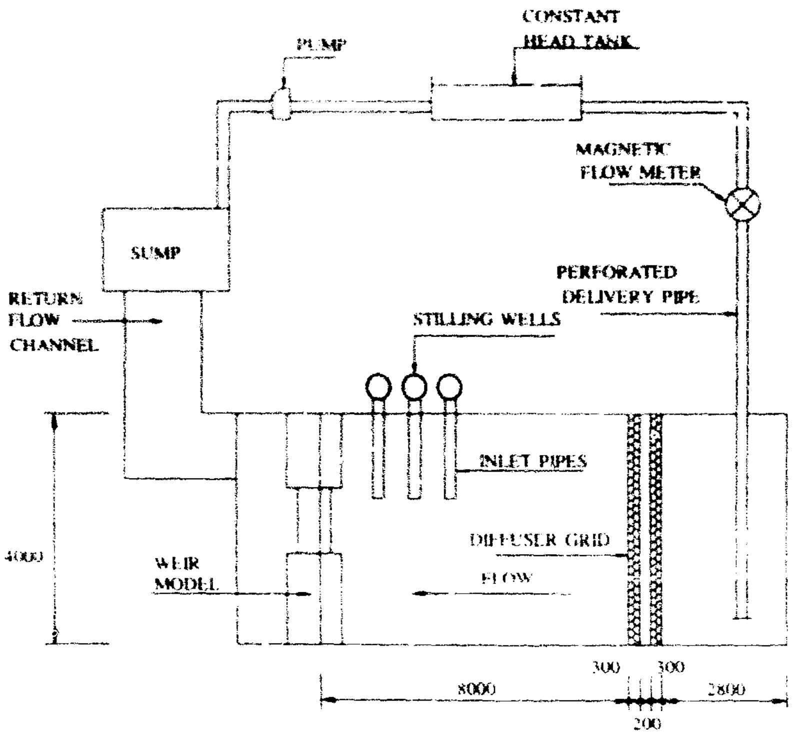


Figure 6.1: *Schematic layout of model as tested in the laboratory of the Department of Water Affairs and Forestry.*

Smooth mortar was used for the construction of the Crump models and pool linings. During all the tests performed the pool cross-section upstream of the model was rectangular. Water levels relative to the low notch level were recorded outside the flow channel in stilling wells by means of point gauges. Water entered the wells through tubes built into the floor of the model. Water levels were measured on top of the crest of the weir and at distances of $2H_{max}$, $4H_{max}$ and $6H_{max}$ upstream of the crest of the low notch by means of point gauges.

The dividing walls used in the tests were fabricated from 10mm thick perspex sheets. These walls projected a distance of $6H_{max}$ upstream of the crest of the weir. In the tests without dividing walls the walls were fixed to the side of the flow channel to ensure that the net overflow length of the weir remained constant.

6.2.3 MODEL FACILITIES AS USED IN THE HYDRAULICS LABORATORY OF THE UNIVERSITY OF STELLENBOSCH.

A schematic layout of the test facility in the hydraulics laboratory of the University of Stellenbosch is included in **Figure 6.2**. Water was supplied to the model via two constant head tanks 5m and 12,5m respectively above the model floor. Two 0,3 m diameter pipes connected these tanks to the model basin. Discharge in the supply pipes was measured by means of two 0,213 m diameter orifice plate gauges connected to either water or mercury manometers. Valves were used to control the discharge in each of the two supply pipes. By using both the supply pipes in parallel a maximum flow rate of approximately 0,4 m^3/s could be achieved.

Return flows in the model were also gauged in the return flow channel with a thin-plate weir. This weir was 0,8 m wide and had a pool depth of 0,5 m. The return flow was measured to obtain an independent check on the discharges gauged with the orifice plates in the supply pipes.

A grid system was again used to ensure uniform flow conditions, whilst surface disturbances were dampened with a floating lattice network. An approach channel of 9m long and approximately 3m wide was used for the model tests. The thin-plate weir models were fabricated from 7mm thick PVC sheeting mounted in a metal frame. Once again, Crump weir models were constructed from smooth concrete. For both the thin-plate and Crump weir models 10mm thick PVC sheeting mounted on a metal frame was used for the dividing walls extending a distance of at least $6H_{max}$ upstream of the model crest. Only two crest levels were modelled in each test; a low crest with a higher crest symmetrically placed on both sides of the low notch.

Water levels relative to the crest of the low notch were measured with a point gauge mounted on a beam. Levels were recorded on the weir crests of the models and at distances of $2H_{max}$, $4H_{max}$ and $6H_{max}$ upstream of both the low and high crests of the weirs.

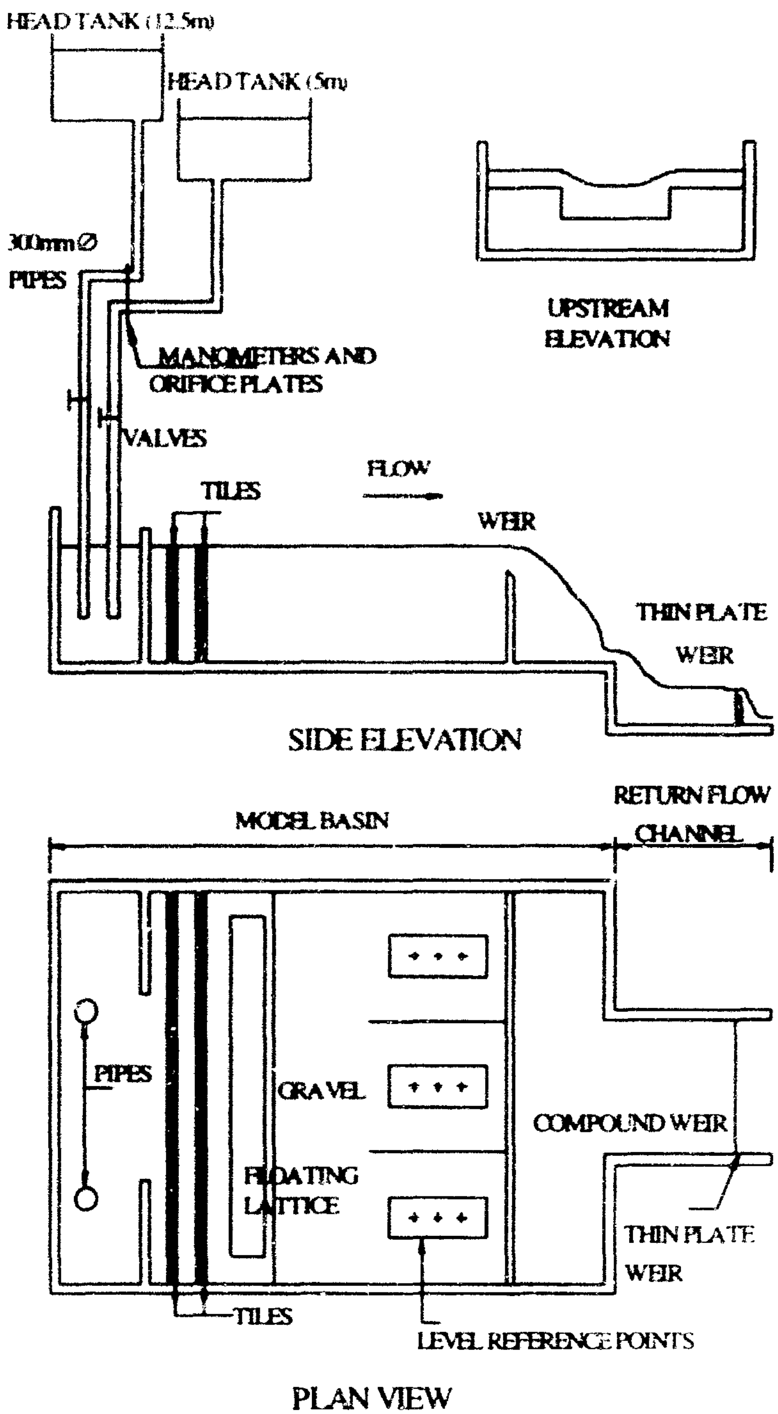


Figure 6.2: *Schematic layout of facilities at the University of Stellenbosch's Hydraulics laboratory.*

6.3 SUMMARY OF THE HYDRAULIC MODEL TEST PROGRAMME AND OBSERVATIONS.

6.3.1 GENERAL.

Water levels were measured at more than one position during the tests, as described in **Chapter 6.2**. In this thesis only the water levels recorded at a distance of four times the maximum total head (H_{max}) upstream of the lowest crest were used to calculate discharge. This was done irrespective of whether dividing walls were used or not. Only the water levels used for the calculation of discharge are tabulated in **Appendix B**. All the measured data is documented in *Laboratory Calibration of Compound Sharp-Crested and Crump Weirs* (Rossouw, et al., 1995).

6.3.2 DEFINITION OF DIMENSIONS.

The different weir dimensions as tested in the model are shown in **Figure 6.3**.

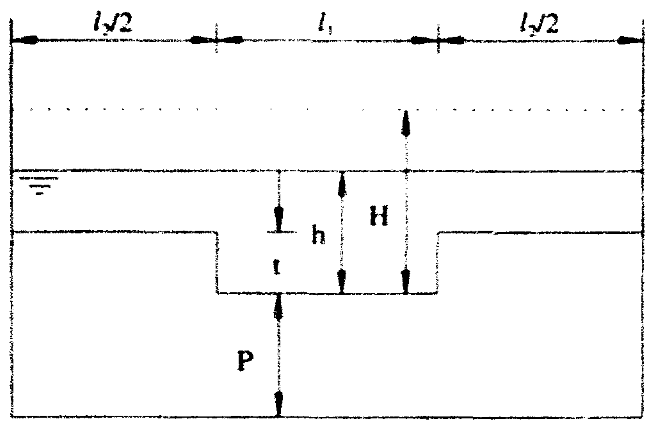


Figure 6.3: *Definition of dimensions as tested in test models.*

The parameters are defined as follows:

- P = Pool depth below the low notch crest level.
- t = Difference in height between the adjacent crests of the compound weir.
- l_1 = Length of the low notch.

- l_2 = Total length of the high crest.
- h = Recorded head relative to the low notch level.
- H = Total head relative to the low notch.

6.3.3 MODEL TESTS WITH CRUMP WEIRS.

6.3.3.1 Model Tests Performed In The Laboratory Of DWAF.

In this series all the model tests were performed with and without dividing walls. During the test series the parameters shown in **Figure 6.3** were varied as per **Table 6.1** below. All the tests were conducted under modular flow conditions with a rectangular approach channel upstream of the compound weir.

Although water levels were measured at more than one position during these tests only the levels recorded at a distance $4H_{max}$ upstream of the crest of the low notch were used to determine discharge. Using only this water level to determine discharge is in agreement with the standards set in South Africa by the Department of Water Affairs and Forestry. All the measurements taken at this position for the different Crump weir configurations tested in Pretoria are given in **Appendices B1 and B2**. **Appendix B1** reflects the data for the tests with dividing walls, whilst **Appendix B2** contains the data for the tests without dividing walls.

Parameter	Range tested
l_1 (m)	$0{,}672 \le l_1 \le 1{,}597$
l_2 (m)	$2{,}408 \le l_2 \le 3{,}332$
P (m)	$0{,}093 \le P \le 0{,}269$
t (m)	$0{,}071 \le t \le 0{,}099$
Q (m^3/s)	$0{,}005 \le Q \le 0{,}177$

Table 6.1: *Range of Crump weir dimensions tested in the DWAF laboratory.*

6.3.3.2 Tests Performed In The Laboratory Of The University Of Stellenbosch.

The main purpose of the model tests on Crump weirs at Stellenbosch was to extend the range of parameters that were previously tested in Pretoria. This was possible due to the greater maximum discharge of 400 l/s available in the laboratory at Stellenbosch. The flow channel used in the tests at Stellenbosch was also narrower compared to the channel used in Pretoria. By testing in two locations independent verification of the data could also be achieved.

All these tests on the Crump weir were performed with and without dividing walls. All the tests were conducted under modular flow conditions with a rectangular shaped approach channel. During the test series the parameters shown in **Figure 6.3** were varied approximately as per **Table 6.2**

Parameter	Range tested
l_1 (m)	$0{,}479 \leq l_1 \leq 1{,}197$
l_2 (m)	$1{,}780 \leq l_2 \leq 2{,}498$
P (m)	$0{,}098 \leq P \leq 0{,}171$
t (m)	$t = 0{,}107$
Q (m^3/s)	$0{,}050 \leq Q \leq 0{,}400$

Table 6.2: *Range of Crump weir dimensions tested in the laboratory of the University of Stellenbosch.*

The observations used for the calculation of discharge in these tests are given in **Appendices B3** and **B4** respectively for Crump weirs with and without dividing walls.

6.3.4 MODEL TESTS WITH THIN-PLATE WEIRS.

All the model tests with thin-plate weirs were run in the hydraulics laboratory of the University of Stellenbosch. These tests on compound thin-plate weirs were all conducted under modular flow conditions.

For all these model tests on compound thin-plate weirs a rectangular approach channel was used. In this series of tests all the weir configurations were tested with and without dividing walls. During this test series the parameters as defined in **Figure 6.3** were varied in the approximate ranges as per **Table 6.3** below.

The data for these different thin-plate weir configurations tested is given in **Appendices B5** and **B6**. **Appendix B5** contains the data for the tests with dividing walls and **Appendix B6** the data for the tests without dividing walls.

Parameter	**Range tested**
l_1 (m)	$0{,}500 \leq l_1 \leq 1{,}180$
l_2 (m)	$1{,}750 \leq l_2 \leq 2{,}430$
P (m)	$0{,}050 \leq P \leq 0{,}300$
t (m)	$0{,}050 \leq t \leq 0{,}200$
Q (m^3/s)	$0{,}050 \leq Q \leq 0{,}400$

Table 6.3: *Range of dimensions tested in model tests on compound thin-plate weirs.*

7. ANALYSIS OF THE MODEL TEST RESULTS.

7.1 GENERAL APPROACH FOLLOWED IN THE ANALYSIS OF THE HYDRAULIC MODEL DATA.

The model test data for weirs equipped with dividing walls was analysed first. Only water levels recorded at a point 4 H_{max} upstream of the lowest weir notch were used in the calculation of discharge. Discharge over the compound weirs was determined by assuming a constant total energy head across the full width of the weirs. This head is obtained by adding the velocity head appropriate to the lowest notch, to the observed water level. This method is specified in the relevant British Standard (BSI, 1981). In doing this, the influence of the assumed constant total energy head on the gauging accuracy can be determined. Methods to improve the discharge formulae should be investigated if the accuracy proves to be unacceptable.

The second part in the analysis of the data, is to quantify errors that can be expected in the gauging of flows if dividing walls are omitted. As stated previously, only water levels recorded at a position 4 H_{max} upstream of the lowest weir notch were used in the calculation of discharge. In this case the water level across the full width of the compound weir is assumed to be horizontal. The total energy head is also assumed to be constant and is determined by adding a velocity head, based on the mean approach velocity to the whole structure, to the observed water level. Methods to improve the accuracy of the discharge theory will also be investigated, if necessary.

In the final part of the analysis the influence of non-ideal pool conditions on the rating of a thin-plate weir without dividing walls were investigated. This was done to get some indication of the influence of shallow and irregular pools on the gauging accuracy of sharp-crested weirs.

7.2 ANALYSIS OF THE TEST RESULTS WITH DIVIDING WALLS AND THE DERIVATION OF IMPROVED DISCHARGE FORMULAE.

7.2.1 GENERAL.

In a number of the tests on the Crump weir, discharges were sufficiently low that flow occurred only over the lowest crest of the compound weir. These cases were analysed separately from the tests where three crests passed flows. In the model tests on the thin-plate weirs flow occurred over all the crests modeled.

Water levels were measured between the dividing walls at a distance 4 H_{max} upstream of the crest of the low notch of the weirs.

7.2.2 COMPOUND CRUMP WEIRS WITH FLOW CONFINED TO THE LOW NOTCH.

If water levels are recorded between dividing walls upstream of a weir section, that section of the weir can be treated as a simple weir (BSI, 1981). The discharge over the low notches of the Crump weirs tested can be rated with the discharge formula established for two-dimensional flow conditions. This formula for modular flow conditions reads as follows:

$$Q = C_d \frac{2}{3}\sqrt{\frac{2}{3}g}\ l\ H^{3/2}$$

with $C_d = 1{,}163\left(1 - \frac{0{,}0003}{h}\right)^{3/2}$

The following general limitations apply:

- $h \geq 0{,}06$ m for a crest section of fine concrete or equivalent;
- $P \geq 0{,}06$ m;
- $l \geq 0{,}30$ m;

- $h/P \leq 3{,}5$;
- $l/h \geq 2{,}0$.

The only restriction affecting the tests with discharges confined to the low notch, is the minimum required flow depth of 60 mm above the weir crest. All the level measurements lower than 60 mm were excluded from this initial analysis. Flow over the low notch was determined for all the data points satisfying the restrictions. An example to explain the technique used to calculate the discharge is given in **Appendix C1**. The results of all these calculations are tabulated in **Appendix D1** and are shown in **Figure 7.1**. In this figure the error, expressed as the ratio between the calculated discharge (Q_c) and the actual flow (Q_m), is plotted as a function of H/t. The ratio H/t, where H is the total energy head and t is the step height between the notches, gives an indication of the relative degree of over-topping over the different crests. Flow commences over the second notch when the ratio of H/t exceeds a value of one.

The calculated discharges overestimate the measured discharges on average by 0,7 % with a standard deviation of 2,5 %. From **Figure 7.1** it is obvious that for values of $H/t < 0{,}8$ the general tendency in all tests is to overestimate the actual discharge. The overestimation in the calculated flows becomes less with increasing discharge and the average error for $H/t > 0{,}8$ is only 0,1 %. This decreasing error in the calculated discharge with increasing total energy head, is typical of errors in the measurement of stage.

In all the tests the average of five stage readings, taken at a point $4H_{max}$ upstream of the lowest crest of the weir, was used to calculate the theoretical discharge in the models. Using this method to determine the final stage measurements, the possibility of random reading errors causing an overestimation in flow is reduced. The constant overestimation in flow indicates the presence of a possible systematic error in stage measurements in the models. Although the theoretical discharge overestimates the actual discharge by less than 1 % on average, it was decided to identify and quantify the systematic error in stage measurement, notwithstanding its limited statistical significance.

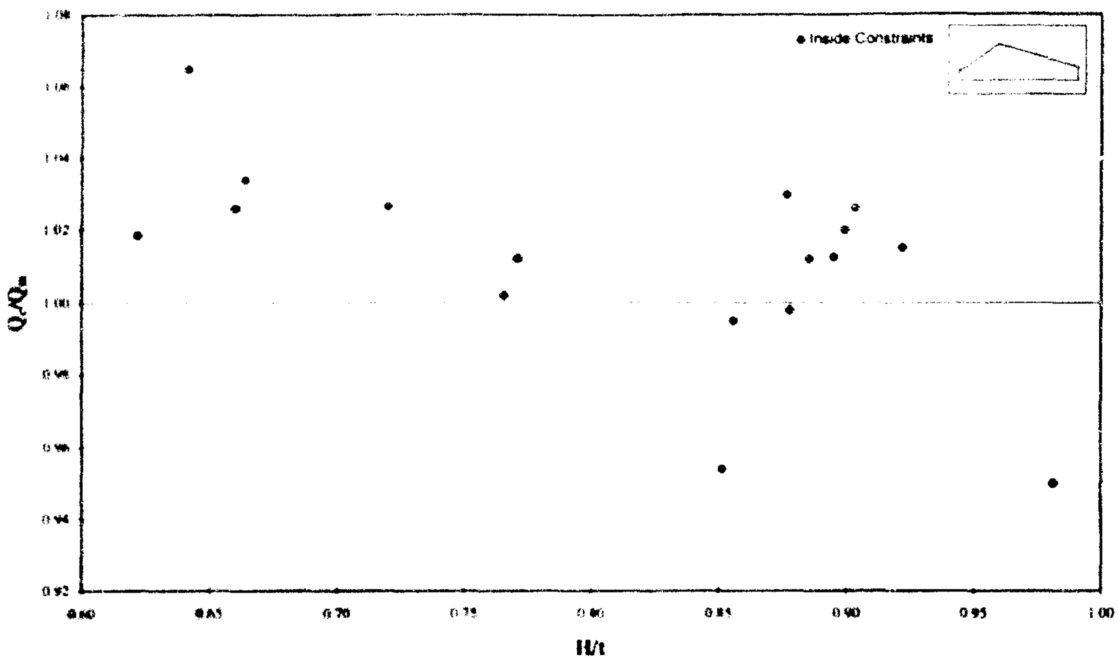


Figure 7.1: *Error in calculated discharge* $\left(Q_c/Q_m\right)$ *expressed as a function of* H/t*; flow confined to the low notch, h > 0.06 m.*

Quantification of the magnitude of errors in the stage readings is the first step in the identification of systematic errors. Subtracting a constant value from the water level measurements until the error in the average theoretical discharge was zero, yielded the magnitude of the systematic error. The size of the systematic error (x) was established as 0,00029 m as given in **Appendix D1**. After compensating for the systematic error the standard deviation of the gauging errors also improved slightly to just below 2,5 %.

This error is of the same order as the correction factor in the discharge coefficient (C_d) of the Crump weir, which allows for the influence of fluid properties at very low heads. The size of this correction factor in the discharge coefficient as given below, is 0,0003 m.

$$C_d = 1{,}163\left(1-\frac{0{,}0003}{h}\right)^{1/2}$$

This led to the assumption that the systematic error in the stage measurements was caused by fluid property effects. As a number of tests were carried out with h < 0,06m, where surface tension effects are noticeable, it was decided to bring this systematic reading error into account. It was noted that the surface tension causes the measured water surface to adhere to the point gauge, as shown in **Figure 7.2**, resulting in too high measured stage values.

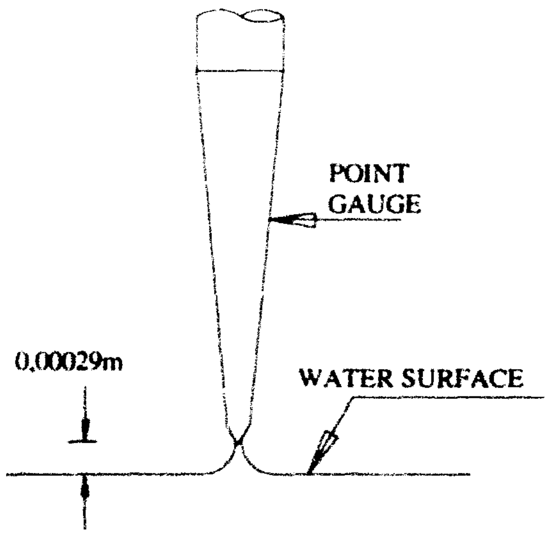


Figure 7.2: *Increased stage reading as a result of surface tension between the point gauge and water surface.*

The calculated discharges for the full data set (including stage measurements less than 60mm over the low notch) overestimate the actual discharges on average by 2,4 % with a standard deviation of 3,6 % without correcting for the systematic error. Having determined the systematic error in stage readings on the data satisfying the criteria of the discharge equation it was corrected for in the full data set. This reduced the average error in the calculated discharge to +1,4 % with a standard deviation of 3,4%. The results of all these calculations for both cases are tabulated in **Appendix D2**. The results of the calculations for the case where the systematic error is deducted from the stage measurements, are shown in **Figure 7.3**. Data points outside the constraints for the application of the Crump weir theory are also shown in this figure. Here adjusted calculated discharge (Q_{cx}) over measured discharge (Q_m) versus adjusted total energy head (H_x) over step height (t) is plotted.

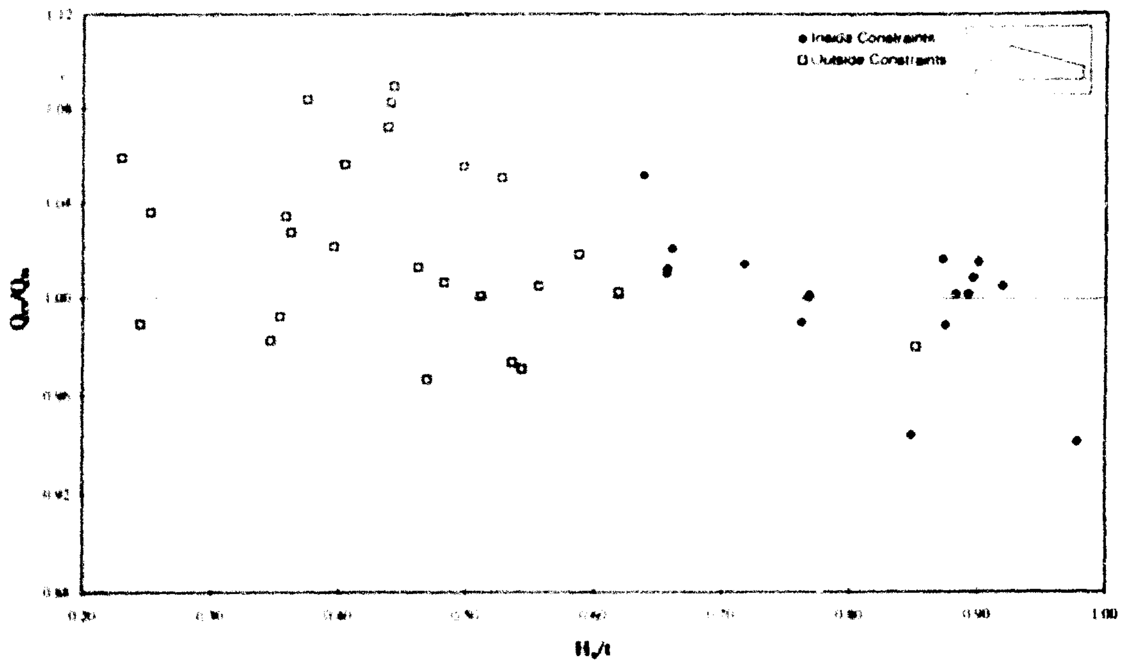


Figure 7.3: *Error in adjusted calculated discharge* $\left(\frac{Q_{x}}{Q_m}\right)$ *expressed as a function of* $\frac{H_{x}}{t}$*, for flow confined to the low notch.*

As the same measuring techniques were used during all the tests the stage measurements given in **Appendix B** were adjusted to accommodate the systematic error of 0,29 mm. This was done because the systematic reading error is of the same order as the correction for fluid property effects in the discharge equation for a Crump weir. All the adjusted stage measurements and the total energy heads and discharges calculated from these adjusted heads, are indicated with an additional subscript "x". The existence of this systematic error for other stage measurement techniques has not been investigated and should therefore be excluded in these cases.

7.2.3 COMPOUND CRUMP WEIRS WITH FLOW OVER ALL THE NOTCHES.

A compound weir equipped with dividing walls may be described as a set of individual weirs operating in parallel. Ideally, water levels should be measured in front of each notch of a compound gauging weir. This presents economical and practical problems and for this reason the upstream head is measured in front of the low notch only in most South African cases. For the purposes of this thesis, the constraints applicable to the discharge formula were only determined based on conditions upstream of the low notch. As long as the flow over the weir is restricted to the low notch, discharge over the weir is calculated as for a simple weir crest. When the higher notches of a compound weir start to operate, it is necessary to make certain assumptions in rating the higher notches. To calculate the discharge over the higher notches of the weir, the total energy head determined upstream of the low notch is assumed to be constant across the full width of the weir (BSI, 1981).

This prescribed method was used to calculate the total discharge when flow occurs over all the notches of the weirs tested. An example to explain this technique for calculating discharge over a compound weir is given in **Appendix C2**. The results of these calculations for all the tests are tabulated in **Appendix D3** and shown in **Figure 7.4**. Once again, the error in flow gauging is expressed as the ratio between the calculated discharge (Q_{cx}) and the actual flow (Q_m), and is plotted as a function of H_1/t.

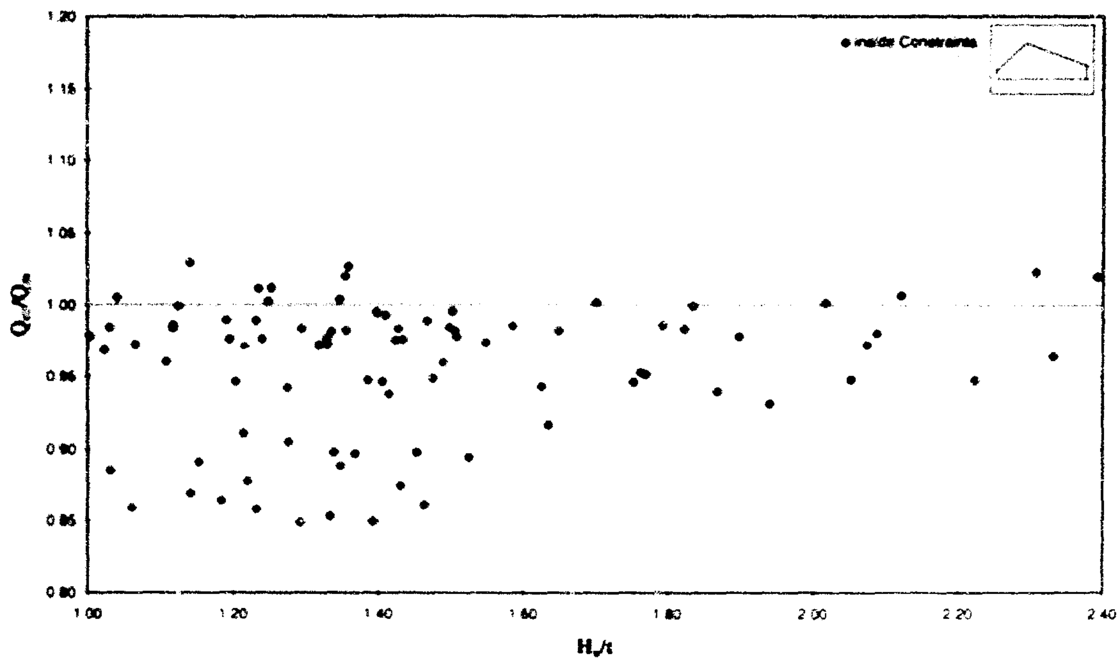


Figure 7.4: *Error in calculated discharge* $\left(Q_{cx}/Q_m\right)$ *expressed as a function of* H_1/t *for flow over all the crests of a compound weir.*

In this case, the calculated discharges underestimate the actual discharges with 4,3 % on average with a standard deviation of 4,8 %. From **Figure 7.4**, it is obvious that there is a general tendency in all the tests to underestimate the actual discharge over the flow range tested. This tendency is most prominent when the higher notch starts to produce flow; this is when $1{,}0 < {}^{H_1}\!/_{t} < 1{,}8$. In one test the actual flow was underestimated by almost 15%. For ${}^{H_1}\!/_{t} \geq 1{,}8$ the accuracy of the calculated discharges improves on average to an underestimation of 2,2%. This is probably due to the flow lines becoming more parallel as a result of the reducing influence of the step height on flow conditions in this region.

The assumption of a horizontal total energy head in front of a weir with dividing walls (BSI, 1981) is clearly incorrect, as shown by the constant underestimation in calculated discharge. Under certain flow conditions the total energy head upstream of the high notches is considerably higher than calculated from the gauged water levels upstream of the low notches of the weirs. From the results given in **Appendix D3**, it is clear that the calculated discharges underestimate the actual flows substantially, especially for values of ${}^{l}\!/_{P} > 0{,}8$; ${}^{l_2}\!/_{l_1} > 2{,}5$ and $1 < {}^{H_1}\!/_{t} < 1{,}8$. In the range specified, the flow conditions at the entrance of the dividing walls to the low notch are strongly three-dimensional. Flow lines at the cutwaters of the dividing walls are curved to the extent that the flow separates from the dividing walls, as shown in **Figure 7.5**.

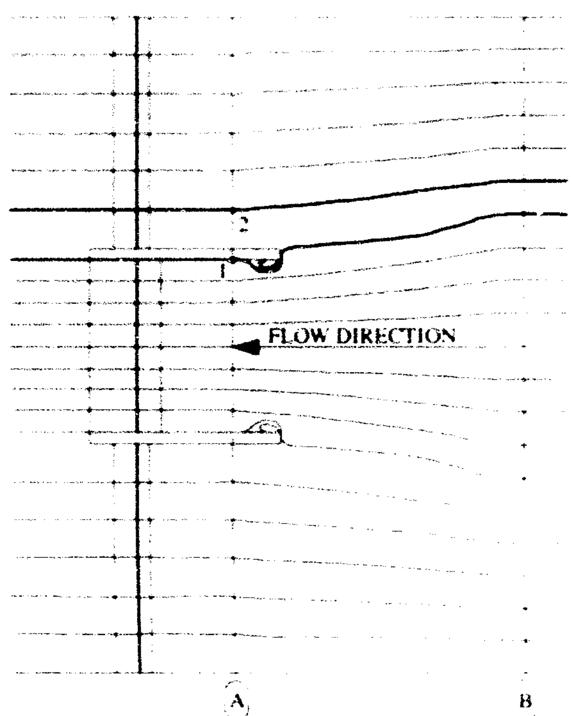


Figure 7.5: *Flow lines near a structure with dividing walls flow over both crests.*

Break-away flow conditions at the cutwaters of the dividing walls, as a result of the three-dimensional flows, cause energy losses at the upstream end of the dividing walls. Assuming uniform flow conditions at section (B) in **Figure 7.5**; the difference in the total energy heads upstream of the low and high notches of a compound weir, at section (A), can be explained as follows.

At section (B), some distance upstream of the dividing walls, the total energy head is assumed to be constant across the width of the river. For a given flow rate the value of the total energy head relative to the low notch, at section (B), is H_T. For the same flow rate a water level h_1 is measured upstream of the low notch, and a level h_2 upstream of the high notch at section (A). The flow conditions at section (A) are defined in **Figure 7.6**.

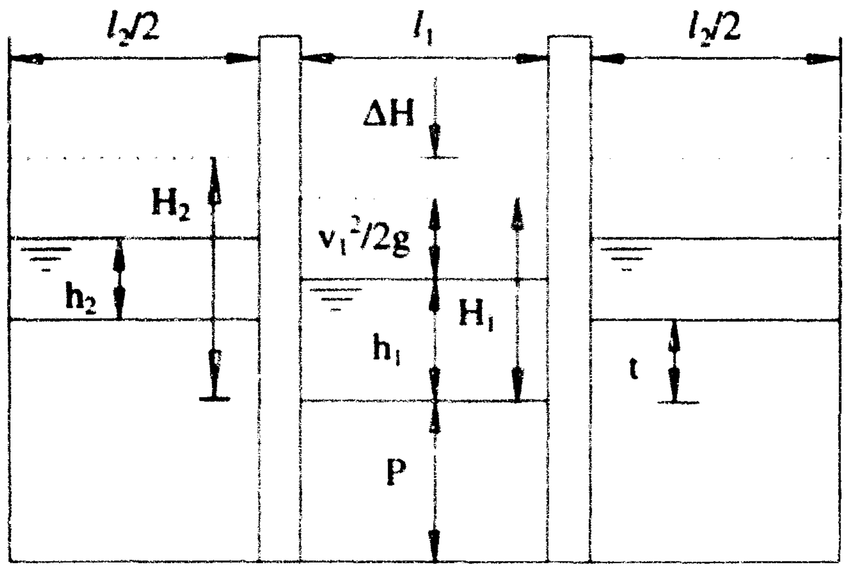


Figure 7.6: *Definition sketch showing the different parameters used in the analysis.*

The total energy head (H_1) upstream of the lowest notch is given by:

$$H_1 = h_1 + \frac{v_1^2}{2g}$$

The total energy head upstream of the high notch (H_2), relative to the low notch, is given by:

$$H_2 = h_2 + \frac{v_2^2}{2g} + t$$

and $H_2 = H_1 + \Delta H$

In this analysis the energy losses due to friction between sections (A) and (B) are assumed to be negligible. Applying the Bernoulli equation between sections (A) and (B) along a stream line in front of the low notch results in:

$$H_1 + k_1 \frac{v_1^2}{2g} = H_T \tag{7.1}$$

where $k_1 \frac{v_1^2}{2g}$ is the total energy loss along the stream line between sections (A) and (B).

Applying the Bernoulli equation between sections (A) and (B) along a neighbouring stream line in front of the high notch, results in:

$$H_2 + k_2 \frac{v_2^2}{2g} = H_T \tag{7.2}$$

where $k_2 \frac{v_2^2}{2g}$ is the total energy loss along the stream line between sections (A) and (B) in front of the high notch.

From equations (7.1) and (7.2) it follows that:

For a specific weir layout one may assume that $v_2 = f(v_1)$ resulting in

$$\Delta H = k_m \left(\frac{v_1^2}{2g} \right) \tag{7.3}$$

$$\therefore k_m = \Delta H 2g \Big/ v_1^2$$

The difference in the total energy heads (ΔH), between the high and low notch, represents the energy losses due to the eddies at the upstream ends of the dividing walls.

Comparison between the calculated and measured discharges yield values of ΔH for each flow modeled. By means of equation (7.3) k_m coefficients for each test discharge were calculated, as can be found in **Appendix D3**. Curves to determine values for k_m were fitted on this data by means of linear regression. These data points and the fitted curves, with the formulae to determine k_m, are shown in **Figure 7.7**.

Line [1] represents k_m coefficients which correct for the influence of energy losses at the entrance to the low notch due to strong three-dimensional flow effects. These conditions occur when the low notch is short relative to the next notch length and where the pool depth approaches the step height. Line [2] describes flow conditions which approach the originally assumed two-dimensional state as $^{H_1}\!/_t$ increases. Line [3] represents conditions when three-dimensional flow effects due to the step and dividing walls have become negligible. In general with increasing flow depth over the higher notch flow conditions become more two-dimensional.

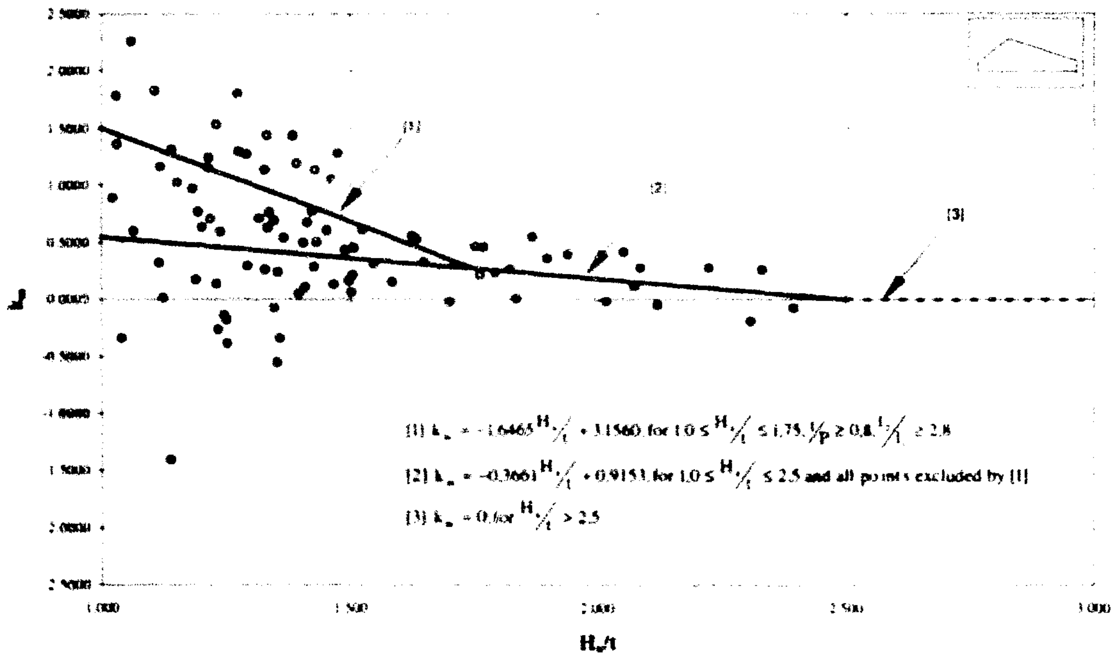


Figure 7.7: *Curves to determine the coefficient (k_m) to calculate ΔH for Crump weirs with dividing walls, flow over both crests.*

Discharges (Q_{ck}) were again calculated for all the tests, using these fitted curves in the calculation of ΔH. These ΔH corrections were used to adjust the total energy head in front of the high notch. Errors in the calculated discharges reduced considerably with the introduction of this correction factor.

Discharge over a compound Crump weir with dividing walls, assuming a horizontal total energy head for the entire weir, is determined as follows:

$$Q_{ck} = Q_1 + Q_2 \qquad \text{Total flow}$$

$$Q_1 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d1} l H_s^{1.5} \qquad \text{Flow over the low notch}$$

$$Q_2 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d2} l_2 \left(H_s - t\right)^{1.5} \qquad \text{Flow over the high notch}$$

With the improved technique the energy heads to determine the flow over the higher notch (Q_2) is adjusted as below in the final iteration of the calculation process.

$$Q_{ck} = Q_1 + Q_2 \qquad \text{Total flow}$$

$$Q_1 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d1} l H_s^{1.5} \qquad \text{Flow over the low notch}$$

$$Q_2 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d2} l_2 \left(H_s - t + k_m\left(\frac{v^2}{2g}\right)\right)^{1.5} \qquad \text{Flow over the high notch}$$

An example to explain this technique to calculate the total discharge over a compound Crump weir with dividing walls is given in **Appendix C3**. The results of all these calculations are also given in **Appendix D5** and shown in **Figure 7.8**. With this improved technique to determine discharge over a compound Crump weir the average error in the calculated discharges is 0,0 % with a standard deviation of 2,9 %. This represents a significant improvement on the statistics of the original calculation method as given in **Appendix D4**.

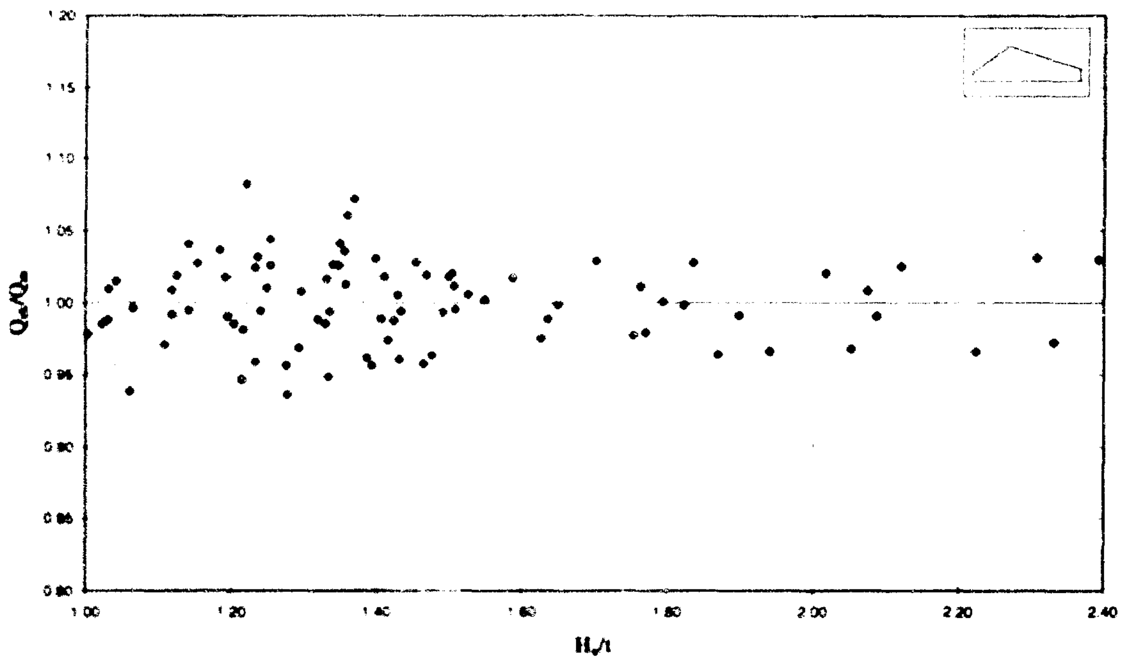


Figure 7.8: *Error in calculated discharge* $\left(Q_{cal}/Q_m\right)$ *expressed as a function of* H_x/t *using the improved calculation technique, flow over both crests.*

7.2.4 COMPOUND THIN-PLATE WEIRS WITH FLOW OVER ALL THE NOTCHES.

In all the tests on the thin-plate weirs all the notches modeled were operational. Both the IMFT and DWAF discharge formulae for thin-plate weirs were used in the analysis of this data.

IMFT Formula (Ackers, et al., 1978)

$$Q = \frac{2}{3} l \sqrt{2g}\left(0{,}627 + 0{,}018\left(\frac{H}{P}\right)\right)H^{1.5}$$

This formula is applicable in the following range:

- $h_1 > 0{,}03$m
- $l > 0{,}2$m
- $P_1 > 0{,}1$m

- $h_1/P_1 < 2,5$

DWAF Formula (Le Roux, et al., 1990)

$$Q = 1,777 \, l \, C_p \, (H + 0,001)^{3/2}$$

Values for the coefficient C_P for this formula can be determined as follows:

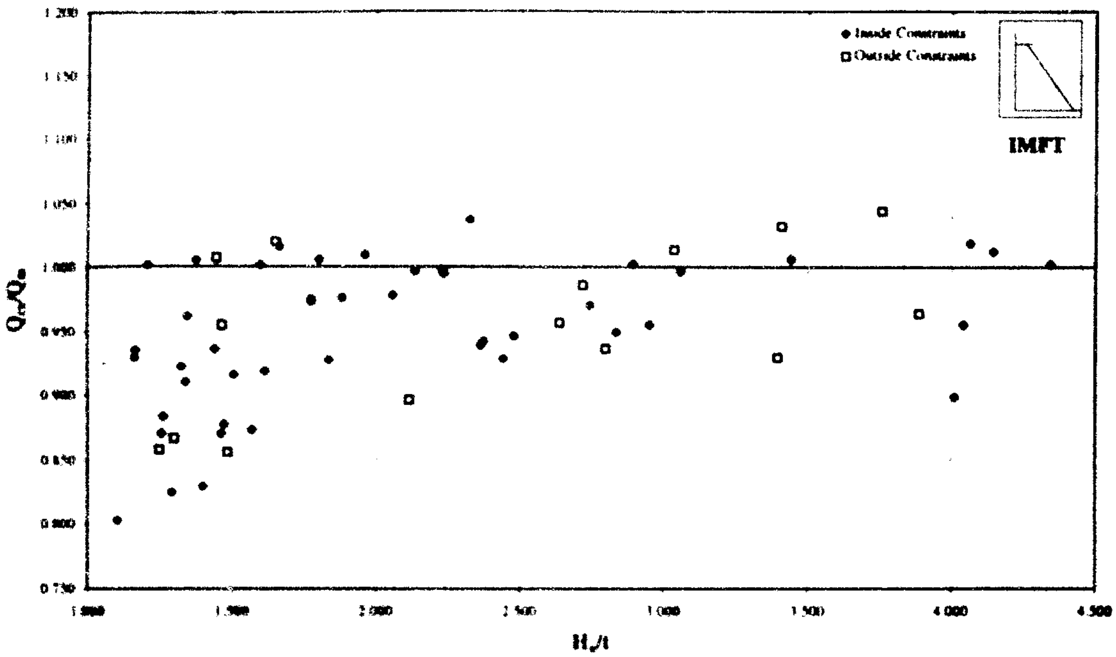
$$C_p = 1,000 + 0,11\left(\frac{H}{H+P}\right)^{1,24} \qquad \text{if} \qquad H/P \le 3,4$$

$$C_p = 1,145\left(\frac{P}{H+P}\right)^{0,04} \qquad \text{if} \qquad 3,4 < H/P \le 200$$

$$C_p = 0,926 \qquad \text{if} \qquad H/P > 200$$

Although it is theoretically possible to use the DWAF equation to rate a sharp-crested weir with a very shallow pool depth (P), the Froude number (Fr) should preferably not exceed a value of 0,4 in the approach channel.

For the purposes of this thesis, the constraints applicable to the discharge formulae were once again determined based on conditions upstream of the low notch only. The IMFT and DWAF formulae will be discussed together to allow comparisons to be drawn. Just as before with the compound Crump weir tests, the total energy head as determined for the calculated flow rate over the low notch was assumed to be horizontal across the entire width of the compound weir. The differences between this constant total energy head level and the crest levels of the higher notches were used to calculate the flows over the high notches of the weirs being tested. Examples of the calculation technique with the IMFT and DWAF formulae can be found in **Appendices C4** and **C6** respectively with the results of the total data sets in **Appendices D4** and **D5** respectively. **Figure 7.9** shows the error in calculated discharge (Q_{cx}) as a ratio between the calculated discharge and the actual discharge (Q_m) versus H_1/t for both discharge formulae.



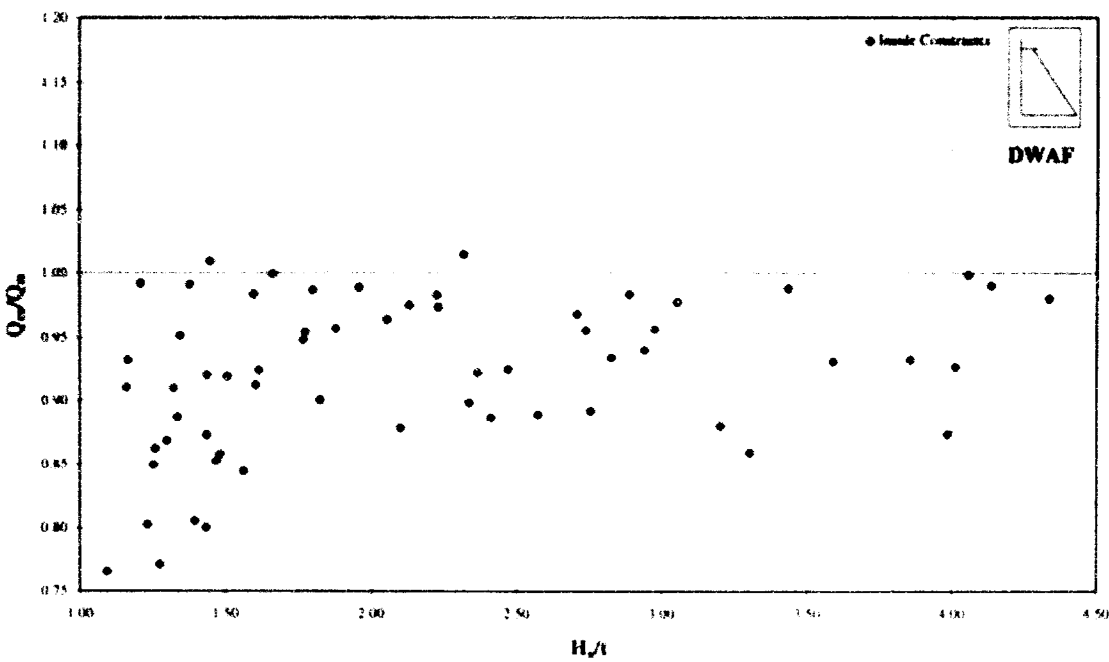


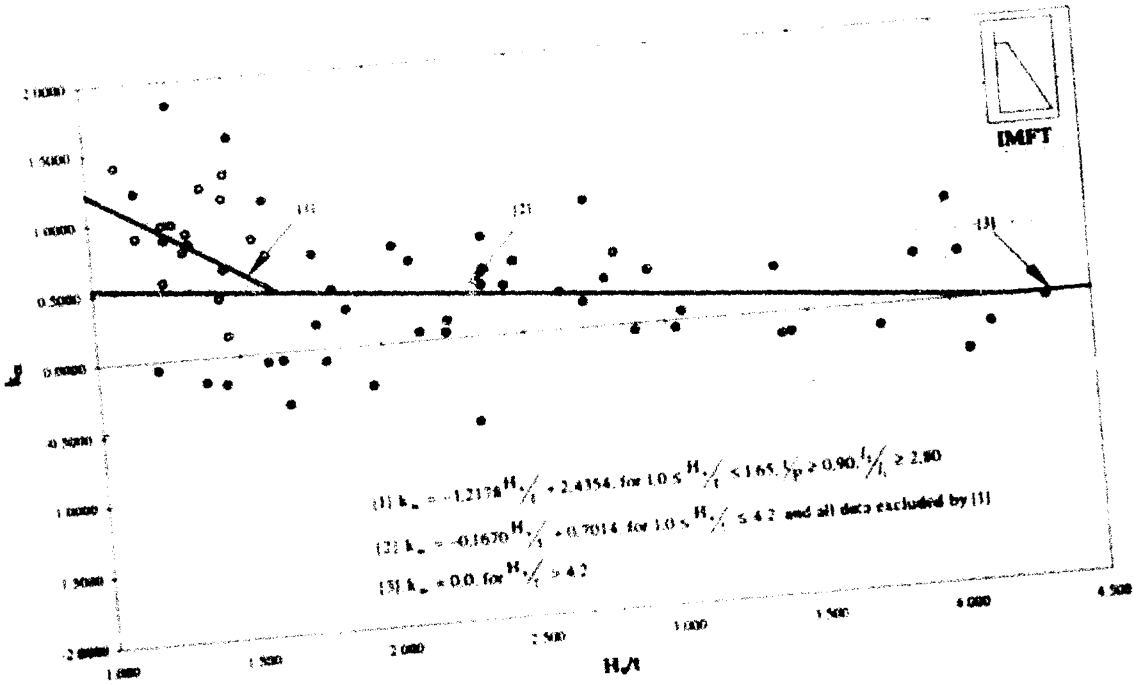
Figure 7.9: *Error in calculated discharge* $\left(\frac{Q_{cs}}{Q_m}\right)$ *expressed as function of* $\frac{H_x}{t}$, *flow over both crests.*

Discharges calculated with the IMFT formula underestimate the actual discharges for nearly the complete flow range tested. As $H_1/_t$ increases $\overline{Q_{c1}/Q_m} \rightarrow 1{,}0$ displaying a similar pattern as the Crump weir, see **Figure 7.4**. On average the calculated discharge underestimates the actual flows which were tested by 4,9% with a standard deviation of 5,7%. Strong three-dimensional flow conditions exist at the entrance of the dividing walls to the low notch, especially in the region $^l/_P > 0{,}9$; $^{l_2}/_{l_1} > 2{,}5$ and $1 < {^{H_1}/_t} < 1{,}8$. In this region considerable underestimations in actual flow occur as a result of a non-horizontal total energy head due to the strongly developed three-dimensional flow conditions.

Discharges calculated with the DWAF formula underestimate the actual flows considerably more than calculated with the IMFT formula over the full range tested. Unlike the IMFT formula, $\overline{Q_{c1}/Q_m}$ does not approach unity, probably due to the different forms of the formulae. On average the calculated discharges underestimate the flows tested by 7,8 %, with a standard deviation of 6,1 %. The similarity between the tests on the thin-plate weirs and that on the Crump weirs becomes more obvious if **Figure 7.9** is examined closely. Underestimations in actual discharge are most prominent in the same region of strongly developed three-dimensional flow conditions as described for the IMFT formula. In one of the tests in the specified range the calculated discharge underestimates the actual flow modeled by nearly 24 %.

The underestimation in flows once again stresses the incorrectness of the assumption of a horizontal total energy head in front of a compound gauging weir with dividing walls. Using the same technique as described in the case of the Crump weir, corrections for the strongly developed three-dimensional flow conditions at the upstream ends of the dividing walls were determined.

For both the IMFT and DWAF formulae values for k_m were determined for all the test results on the compound thin-plate weirs. These calculated values for k_m and the fitted curves with their formulae to determine k_m, are shown in **Figure 7.10** and tabulated in **Appendices D4** and **D5** respectively. Using the fitted curves to determine values for ΔH, discharges (Q_{ck}) were again calculated for all the tests.



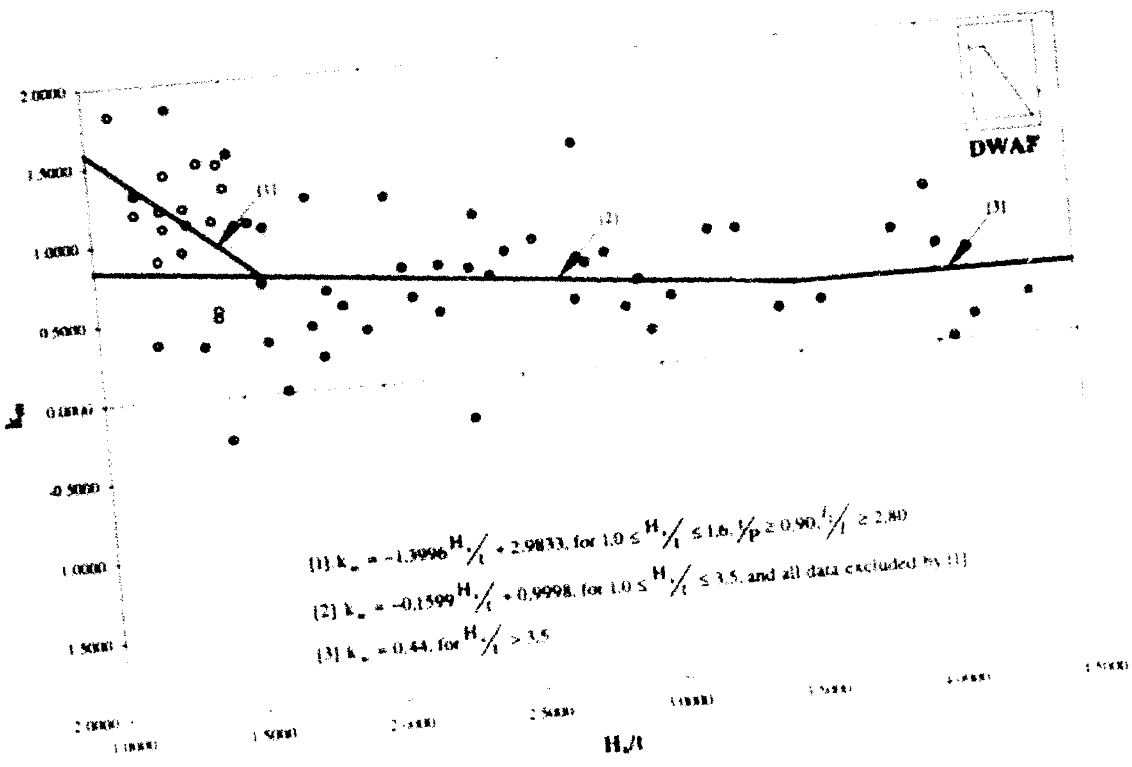


Figure 7.10: *Curves to determine the coefficient (k_m) to calculate ΔH for thin-plate weirs with dividing walls, flow over both crests.*

For both discharge formulae k_m values determined with line [1] correct for the strong three-dimensional flow conditions at the upstream ends of the dividing walls. These conditions occur when the length of the low notch is short relative to the length of the higher notch and where the pool depth approaches the step height between the crests. Line [2] corrects the discharges not strongly influenced by the three-dimensional flow conditions. In both cases line [3] in **Figure 7.10** is applicable when the influence of three-dimensional flow conditions have become negligible. Values of k_m as determined for the DWAF formula are larger than those correcting for three-dimensional flow conditions using the IMFT formula.

As the same data was used in the analyses the differences in the k_m values can only be ascribed to the inherent differences between the two formulae.

Discharge over a compound thin-plate weir with dividing walls, assuming a horizontal total energy head for the entire weir, is determined as follows:

$$\left.\begin{aligned} Q_{cx} &= Q_1 + Q_2 && \text{Total flow} \\ Q_1 &= \frac{2}{3}\sqrt{2g}C_{d1}l_1H_x^{1.5} && \text{Low notch flow} \\ Q_2 &= \frac{2}{3}\sqrt{2g}C_{d2}l_2(H_x - t)^{1.5} && \text{High notch flow} \end{aligned}\right\} \quad \text{IMFT}$$

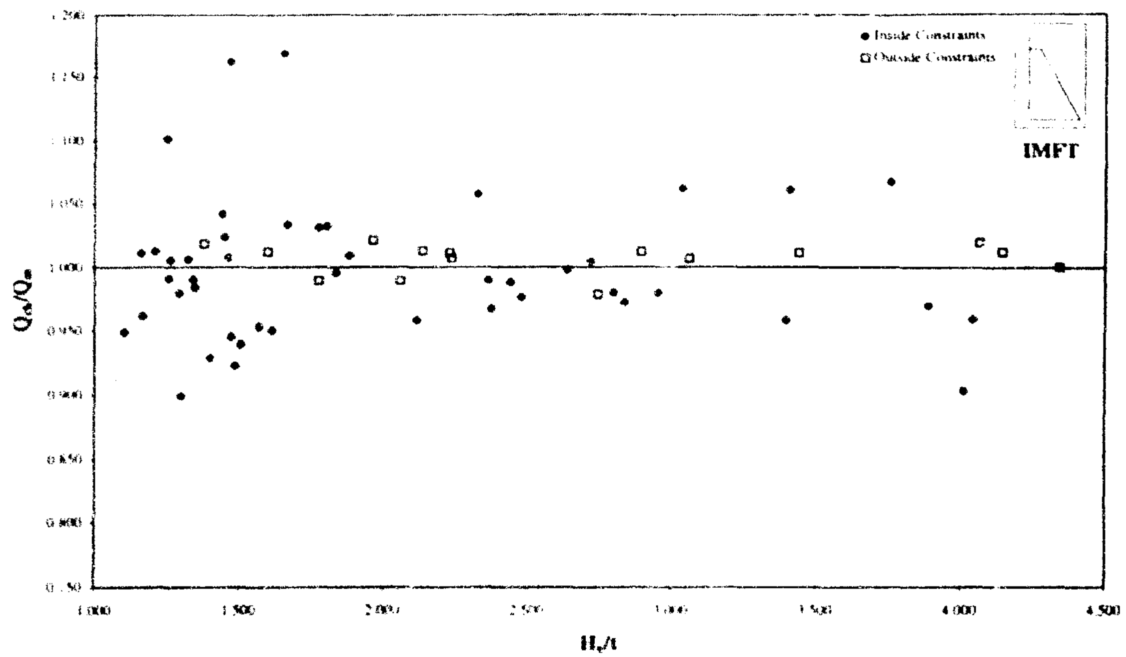
$$\left.\begin{aligned} Q_{cx} &= Q_1 + Q_2 && \text{Total flow} \\ Q_1 &= 1{,}777C_p l_1(H_x + 0{,}001)^{1.5} && \text{Low notch flow} \\ Q_2 &= 1{,}777C_p l_1(H_x - t + 0{,}001)^{1.5} && \text{High notch flow} \end{aligned}\right\} \quad \text{DWAF}$$

With the improved technique, the energy heads to determine flow over the higher notch (Q_2) is adjusted as below, in the final iteration of the calculation process

$$\left.\begin{aligned} Q_{cx} &= Q_1 + Q_2 && \text{Total flow} \\ Q_1 &= \frac{2}{3}\sqrt{2g}C_{d1}l_1H_x^{1.5} && \text{Low notch flow} \\ Q_2 &= \frac{2}{3}\sqrt{2g}C_{d2}l_2\left(H_x - t + k_m\left(\frac{v_1^2}{2g}\right)\right)^{1.5} && \text{High notch flow} \end{aligned}\right\} \quad \text{IMFT}$$

$$
\left.\begin{array}{ll}
Q_{ct} = Q_1 + Q_2 & \text{Total flow} \\
Q_1 = 1{,}777 C_p l_1 (H_x + 0{,}001)^{1,5} & \text{Low notch flow} \\
Q_2 = 1{,}777 C_p l_1 \left(H_x - t + 0{,}001 + k_m \left(\dfrac{v_1^2}{2g} \right) \right)^{1,5} & \text{High notch flow}
\end{array}\right\} \text{DWAF}
$$

Discharges were again calculated with both formulae bringing the correction coefficients k_m, as fitted in **Figure 7.10**, into account to correct for the three-dimensional flow conditions. Examples to explain the technique to correct for the underestimation in total energy head in front of the high notch are given in **Appendices C5** and **C7** for the IMFT and DWAF formulae respectively. The total data sets, taking the corrections into account, are also tabulated in **Appendices D4** and **D5** respectively and shown graphically in **Figure 7.11**. Applying these corrections to the total energy head in front of the high notch the error in the calculated discharges reduces considerably for both formulae. In the case of the IMFT formula the error in the calculated flows was 0,0% on average with a standard deviation of 4,9%. For the DWAF formula, on average, the improved calculated flows underestimated the actual flows with less than 0,1% and a standard deviation of 4,1% indicating that the accuracy of the DWAF formula is comparable to that of the IMFT formula.



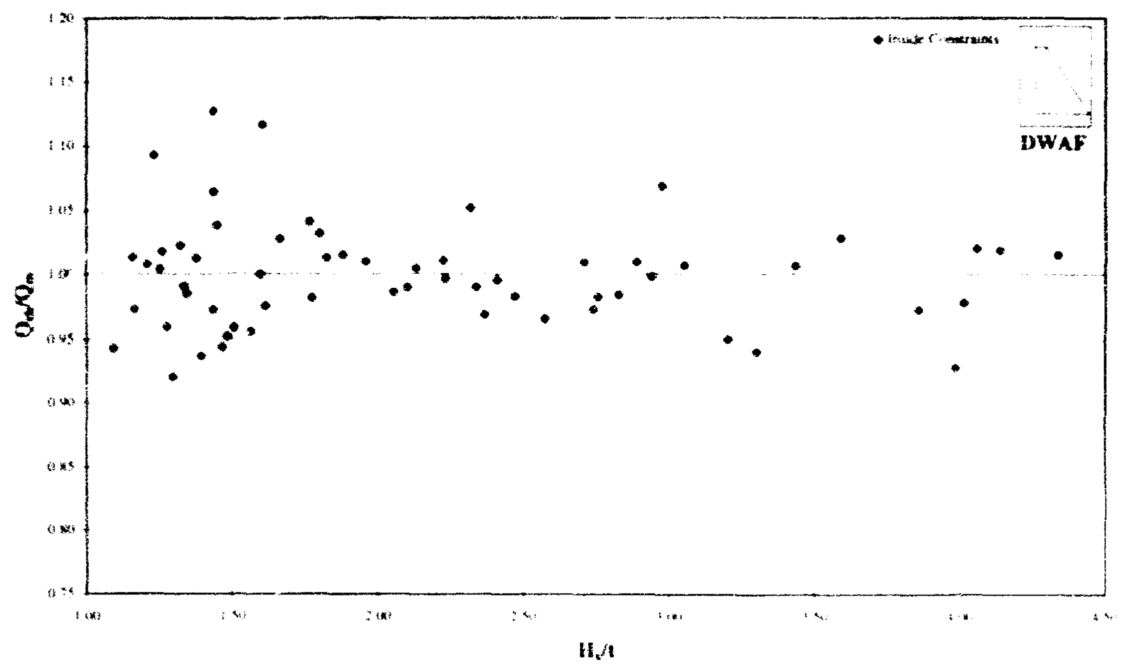


Figure 7.11: *Error in calculated discharge* $\left(Q_{cs}/Q_m\right)$ *expressed as a function of* H_e/t *using the improved calculation technique, flow over both crests.*

7.2.5 CONCLUSIONS.

An assumed horizontal total energy head across the entire width of a compound gauging weir with dividing walls, as per BSI (1981), yields theoretical discharges which underestimate the actual discharges consistently. This occurs as a result of the three-dimensional flow conditions which are present at such structures. Pool depths which are shallow relative to the step height and low notches short relative to the adjacent notches exaggerate these flow conditions. Increasing flow depth over the higher notch reduces the three-dimensional flow effects, resulting in improved accuracy.

Energy losses occur at the upstream ends of the dividing walls due to the break-away flow conditions. Water levels are gauged downstream of these losses and the assumption of a horizontal total energy head upstream of the weir does not compensate for these losses upstream of the remaining notches. Compensating for these losses leads to higher total energy heads in front of the remaining notches, resulting in higher discharges.

This thesis outlines techniques to correct for the three-dimensional flow conditions by compensating for the energy losses. The energy head in front of the higher notches is corrected by adding the relevant k_m value multiplied with the low notch kinetic energy head to the assumed horizontal total energy head previously used in the discharge equations. Formulae to determine coefficients to correct for the energy losses at compound Crump and thin-plate weirs with dividing walls, were determined. It is recommended that these corrections should be applied in the calibration of compound gauging weirs with dividing walls, if water levels are only measured in front of the lowest notch.

7.3 ANALYSIS OF THE TEST RESULTS WITHOUT DIVIDING WALLS AND DERIVATION OF IMPROVED DISCHARGE FORMULAE.

7.3.1 GENERAL.

It is general practice in South Africa to gauge flows with compound weirs without dividing walls and to record water levels at a distance of 4 H_{max} upstream of the crest of the low notch. Gauging of flows in rivers by means of structures without dividing walls does not conform to the standards set by the British Standards Institution (1981). It was therefore necessary to determine the magnitude of errors which are made if flows are gauged with such structures and to adjust the discharge formulae where necessary.

In a number of the tests on the Crump weir, discharges were limited to the lowest crest of the compound weir. Although these tests were analysed separately from those where flow occurred over all the notches, the results of all these tests on compound Crump weirs are discussed together.

The thin-plate weirs were only tested for conditions where flow occurred over all the notches modeled. Only two notches were modeled, regardless of the type of structure tested. Measured water levels in this section of the analysis were all adjusted to allow for the systematic reading error in the head measurements during the tests.

7.3.2 COMPOUND CRUMP WEIRS WITHOUT DIVIDING WALLS.

The British Standards Institution (BSI, 1981) states that all compound gauging weirs without dividing walls should be calibrated in situ or by model analyses. Most of the gauging weirs in South African rivers have been constructed without dividing walls and only a few have been calibrated in situ by using current meters. The general calibration theory of a Crump weir is used to rate compound Crump weirs without dividing walls. In order to apply the theory it was necessary to make the following assumptions:

- Water surface level as gauged upstream of the low notch of the weir is horizontal across the width of the river.

- Horizontal total energy head upstream of the weir across the width of the river

- Total flow cross-section area normal to the flow direction is used to determine the approach velocity upstream of the weir.

An example to explain the technique used to calculate flows over a compound Crump weir without dividing walls is given in **Appendix E1**. The results of the tests with flows confined to the low notch of the weirs are tabulated in **Appendix F1**, whilst the results of the tests with flows over all the weir crests are given in **Appendix F2**. The results of all these calculations are plotted in **Figure 7.12**. In this figure the error, expressed as the ratio between the calculated discharges (Q_{cs}) and the actual discharges (Q_m), is plotted as a function of $^{H_s}/_t$. For values of $^{H_s}/_t$ < 1,0 flow is confined to the low notch of the weir. Flow commences over the higher notches of the weirs when this ratio exceeds a value of one.

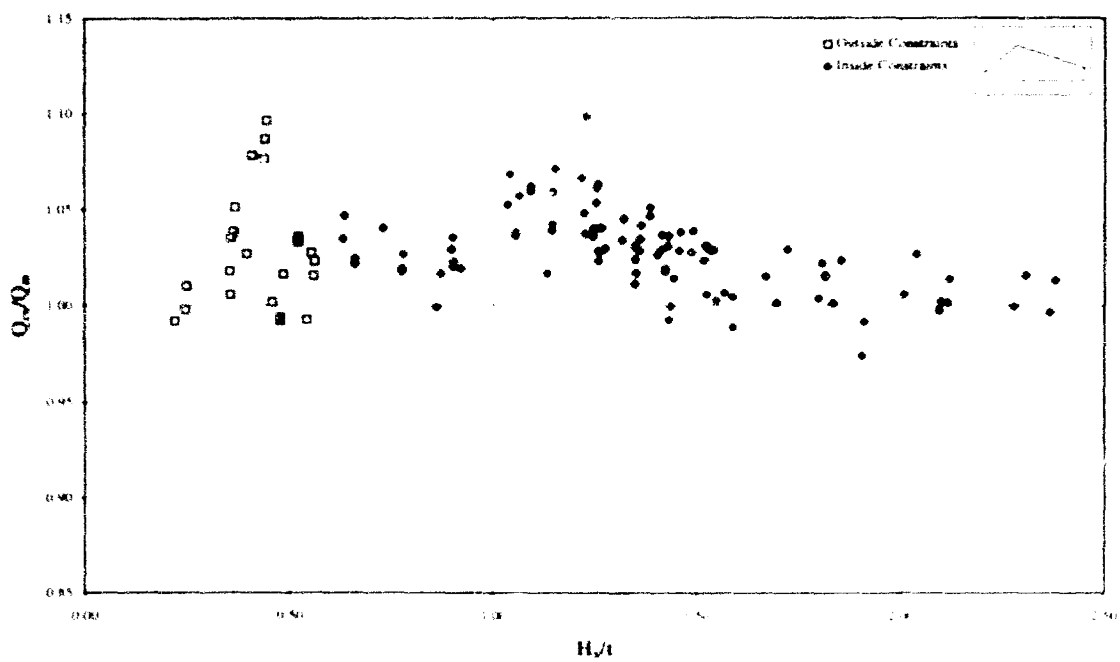


Figure 7.12: *Error in calculated discharge* $\left(^{Q_{cs}}/_{Q_m}\right)$ *expressed as a function of* $^{H_s}/_t$ *for the complete test series.*

For flows confined to the low notch of the weirs the calculated discharges overestimate the flows modeled on average by 2,7 % with a standard deviation of 2,4 %, as seen on

Figure 7.12. Considering only flows inside constraints an average overestimation of 2,5 % with a standard deviation of 1,0 % occurs.

For values of $^{H_1}/_t$ just greater than one, the calculated discharges overestimate the actual flows which were tested with more than 5 %. However, the magnitude of this overestimation in discharge decreases as the flow depth over the high crests of the weirs increases as can be seen in **Figure 7.12**. When $^{H_1}/_t > 1,0$ the calculated discharges overestimate the actual flows modeled on average by 2,8 % with a standard deviation of 2,2%.

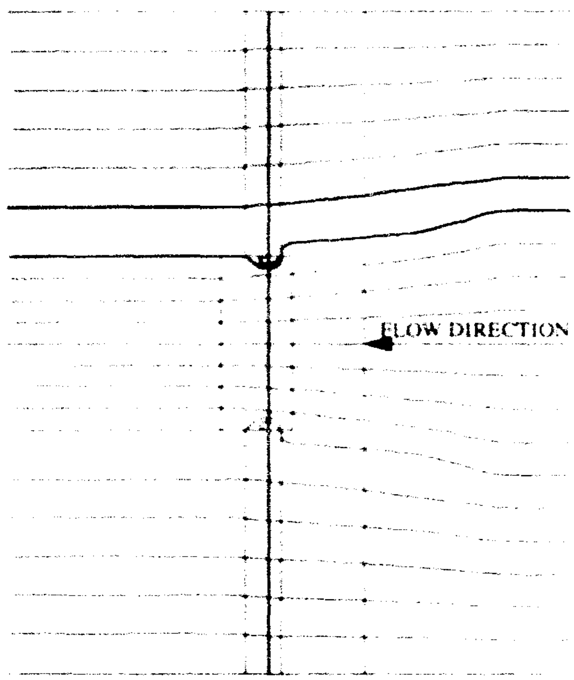


Figure 7.13: *Flow lines near a structure without dividing walls; flow over both crests.*

The tendency for the calculated discharges to overestimate the actual flows can be explained with the aid of **Figure 7.13**. In this figure the flow conditions upstream of a Crump weir without dividing walls are shown. Although the flow conditions are uniform with parallel flow lines at the position where the water levels are recorded, three-dimensional flow conditions exist just upstream of the weir crest. These three-dimensional flow conditions induce strongly curved flow lines at the point where the high and low notch meet. Energy losses occur near the weir crest due to these curved flow conditions. To compensate for these losses the water surface upstream of the crest rises.

These energy losses, due to three-dimensional flow conditions, were not brought into consideration during the derivation of the original two-dimensional discharge formula used in the compilation of **Figure 7.12**. These losses cause the discharge formula to overestimate the actual discharges. As flows increase, the three-dimensional flow conditions reduce at the weir crest as the flow lines become more parallel across the structure. In **Figure 7.12** it can be seen for $H_x/t > 2{,}0$ that $\overline{Q_{cx}/Q_m} \rightarrow 1{,}0$; confirming the more uniform flow conditions.

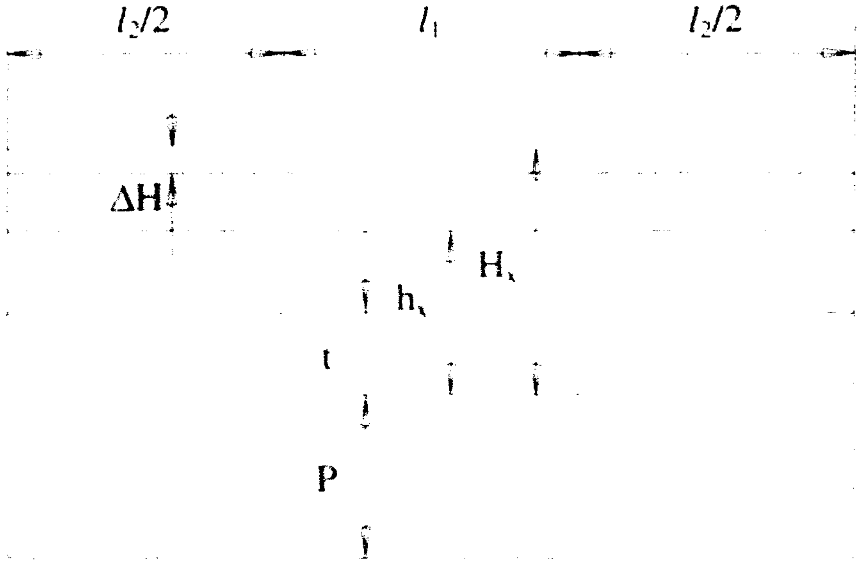


Figure 7.14: *Definition sketch showing the correction ΔH in the total energy head.*

Since three-dimensional flow conditions result in a raised water surface and thereby an overestimation in total energy head, it is logical to bring in a correction (ΔH) for this error in the total calculated energy head (H_x), as shown in **Figure 7.14**. Comparison between the calculated and measured discharges yield values of ΔH for each flow measured. For each flow rate tested, the dimensionless ratio $\Delta H/H_x$ was calculated and curves to determine this ratio as a function of H_x/t were fitted to these data points, by means of linear regression. These data points, the fitted curves and the formulae to determine $\Delta H/H_x$ are shown in **Figure 7.15**. For values of $H_x/t > 2{,}3$, $\Delta H/H_x = 0{,}0$ in this fitted line, confirming the reduced influence of the three-dimensional flow conditions at high stage values.

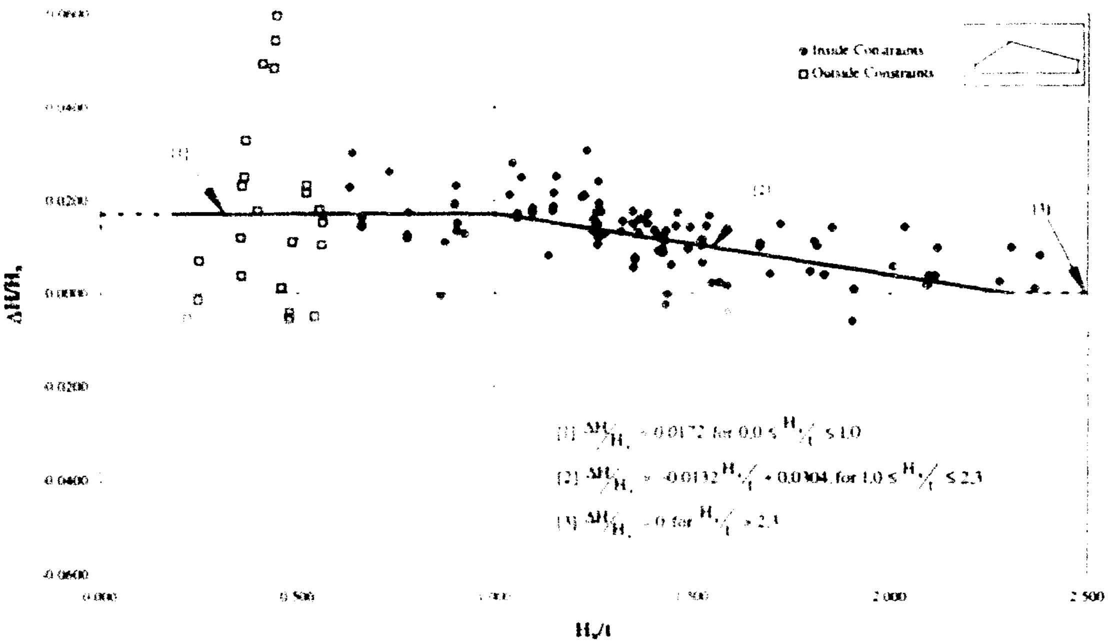


Figure 7.15: *Curves to define the ratio* $\Delta H/H_s$ *expressed as a function of* H_s/t *, all test series.*

In **Figure 7.15**, line [1] represents the effect of three-dimensional flow conditions as stage increases above the low notch. The energy loss at the weir crest (ΔH), due to three-dimensional flow conditions is a function of the velocity at the weir crest. In this region $\Delta H/H_s$ tends to be constant and may be explained as follows:

> Flow conditions change from subcritical to supercritical as flow passes over the weir crest. This implies that critical flow conditions exist in the vicinity of the crest. At a critical flow section of unit width the total energy head is equivalent to 1,5 times the critical flow depth (h_c) and 3 times the kinetic energy $\left(v^2/2g \right)$.

$$\frac{\Delta H}{H_s} = \frac{k\, v^2/2g}{H_s}$$

and

$$H_x = 3\left(\frac{v_x^2}{2g}\right)$$

$$\therefore \frac{\Delta H}{H_x} \propto \frac{k\,\frac{v_x^2}{2g}}{3\,\frac{v_x^2}{2g}}$$

$$\therefore \qquad \propto k$$

The three-dimensional flow effects reduce as shown in line [2] with increasing discharge over the higher notch. $\Delta H/H_x$ is assumed to be zero for $H_x/t > 2{,}3$ as shown in line [3] where the flow lines become nearly parallel over the structure.

Values for ΔH were calculated for all the tests, as given in **Figure 7.15**. These ΔH corrections were subtracted from the total energy head in front of the entire weir. Discharges ($Q_{\Delta H}$) were again calculated by using the adjusted total energy heads. Errors in the calculated discharges were considerably reduced with the introduction of this correction factor.

Discharge over a compound Crump weir without dividing walls, assuming a horizontal water surface and total energy head for the entire weir, is calculated as follows:

$Q_{ex} = Q_1 + Q_2$	Total flow
$Q_1 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d1} l H_x^{1.5}$	Flow over the low notch
$Q_2 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d2} l_2 (H_x - t)^{1.5}$	Flow over the high notch

With the improved technique the total energy head to determine the flow over the compound weir ($Q_{\Delta H}$) is adjusted as below in the final iteration of the calculation process.

$Q_{\Delta H} = Q_1 + Q_2$	Total flow
$Q_1 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g} C_{d1} l (H_x - \Delta H)^{1.5}$	Flow over the low notch

$$Q_2 = \left(\frac{2}{3}\right)^{1.5} \sqrt{g}\, C_{d2}\, l_2 \left(H_1 - t - \Delta H\right)^{1.5} \qquad \text{Flow over the high notch}$$

An example illustrating the technique to rate a weir by bringing the correction factor, ΔH, into account is given in **Appendix E2**. The results of these calculations are tabulated in **Appendices F1** and **F2** respectively for flows only over the low notch and for flows over all the weir crests. The results of the improved discharge calculation method are also shown in **Figure 7.16**. With this improved calculation technique the calculated discharges overestimate the actual flows with less than 0,1 % with a standard deviation of 2,3 % for flows confined to the low notch of the weir. For flow over all the crests of a compound Crump weir the calculated discharges and actual discharges underestimated the actual flows with less than 0,1 % with a standard deviation of 1,5 %.

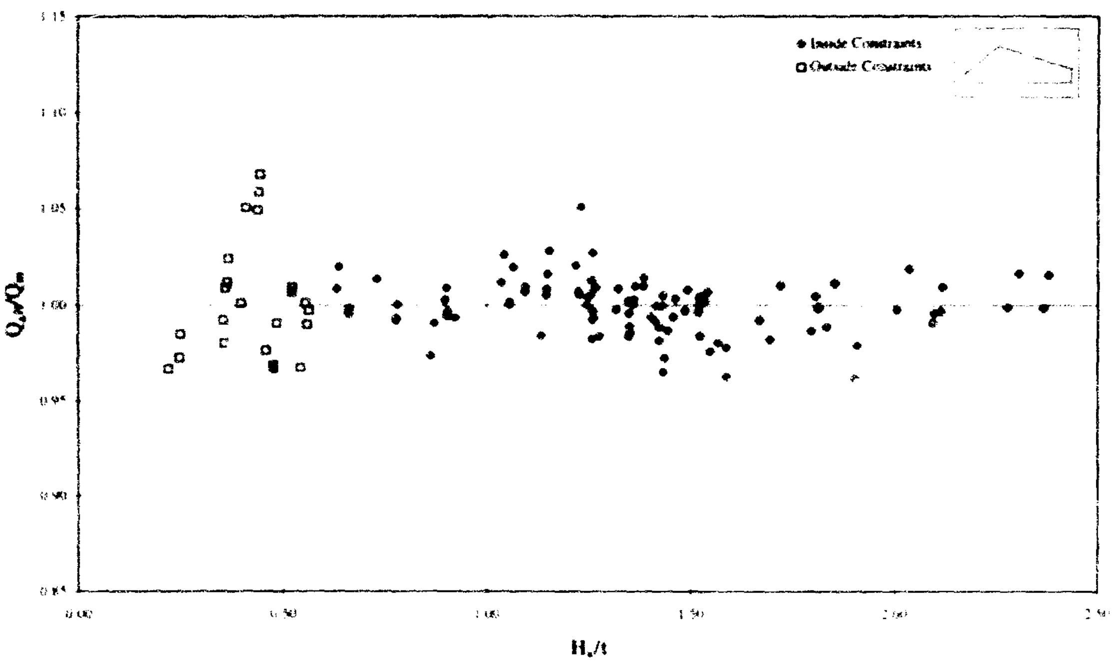


Figure 7.16: *Error in calculated discharge* $\left(Q_{\Delta H}/Q_m\right)$ *expressed as a function of* H_1/t *using the improved calculation technique.*

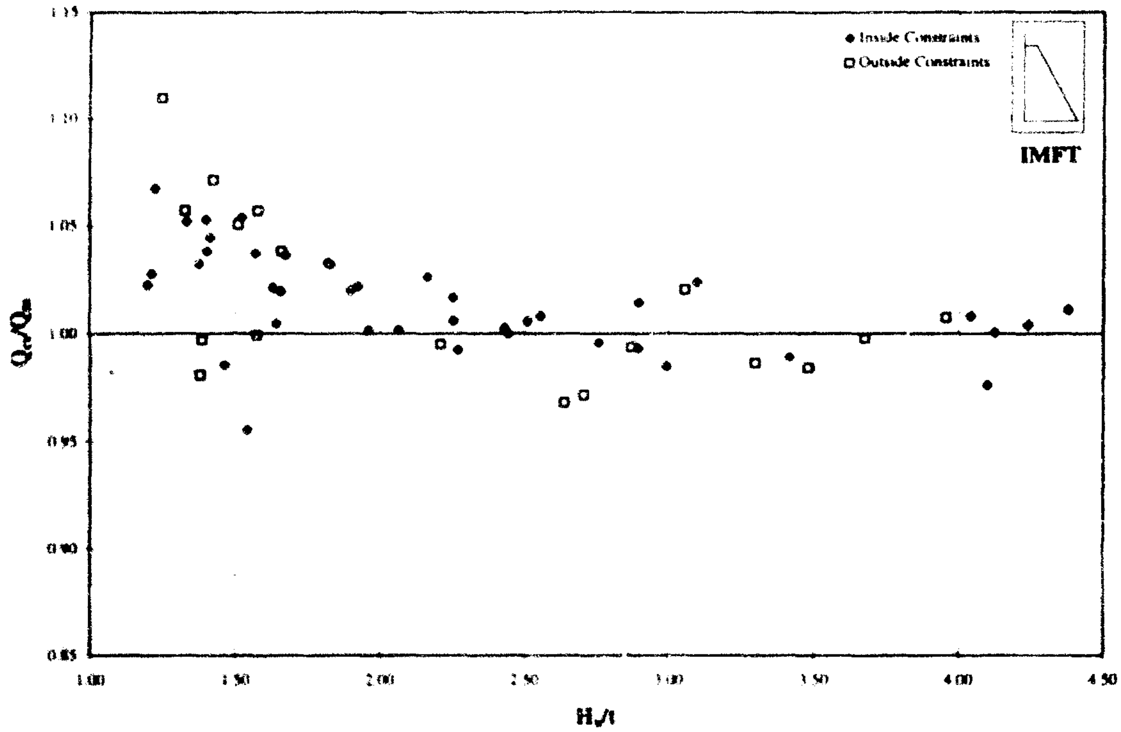
7.3.3 COMPOUND THIN-PLATE WEIRS WITHOUT DIVIDING WALLS.

As mentioned previously flow occurred over both crests during all the tests on the thin-plate weirs. Both the IMFT and DWAF discharge formulae were used in the analysis of this data. For purposes of comparison the IMFT and DWAF formulae will be discussed simultaneously. The same assumptions used in the rating of compound Crump weirs without dividing walls are applicable to the rating of thin-plate weirs without dividing walls:

- Water surface level as gauged upstream of the low notch of the weir is horizontal across the width of the river.
- Horizontal total energy head upstream of the weir across the width of the river.
- Total flow cross section normal to the flow direction is used to determine the approach velocity upstream of the weir.

The calculated flows, based on the above assumptions, are tabulated in **Appendices F3** and **F4** for the IMFT and DWAF formulae resp...ively and shown in **Figure 7.17** for the total data set. This figure shows the error in the calculated discharge (Q_{cx}) as a ratio of the actual discharge (Q_m) versus H_1/t. Sample calculations to explain the method used to determine discharge over a compound thin-plate weir without dividing walls are given in **Appendices E3** and **E5** respectively.

Discharges calculated with the IMFT formula (Q_{cx}) overestimate the actual discharges (Q_m), on average, especially in the early stages of flow over the higher notch. As H_1/t becomes greater than 2,5 the average error in calculated discharge diminishes, $\overline{Q_{cx}/Q_m} \rightarrow 1{,}0$. An average overestimation of 1,5% with a standard deviation of 2,8% is found over the full range of models tested. In the worst case, where flow had just started over the higher notch, an overestimation of 11% was recorded.



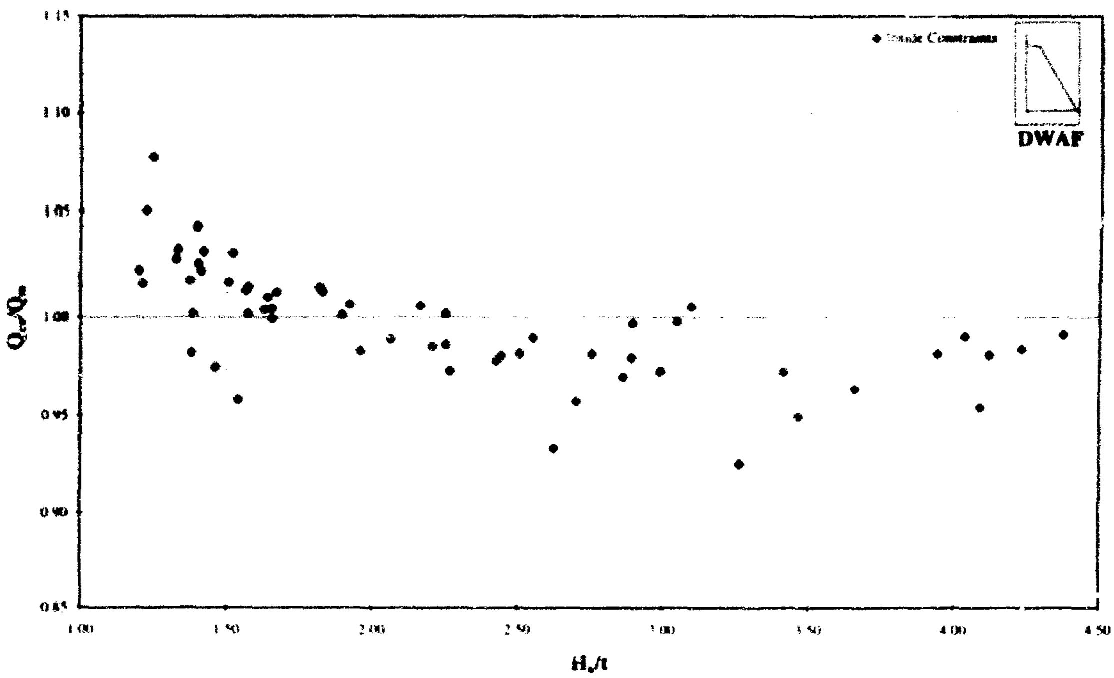


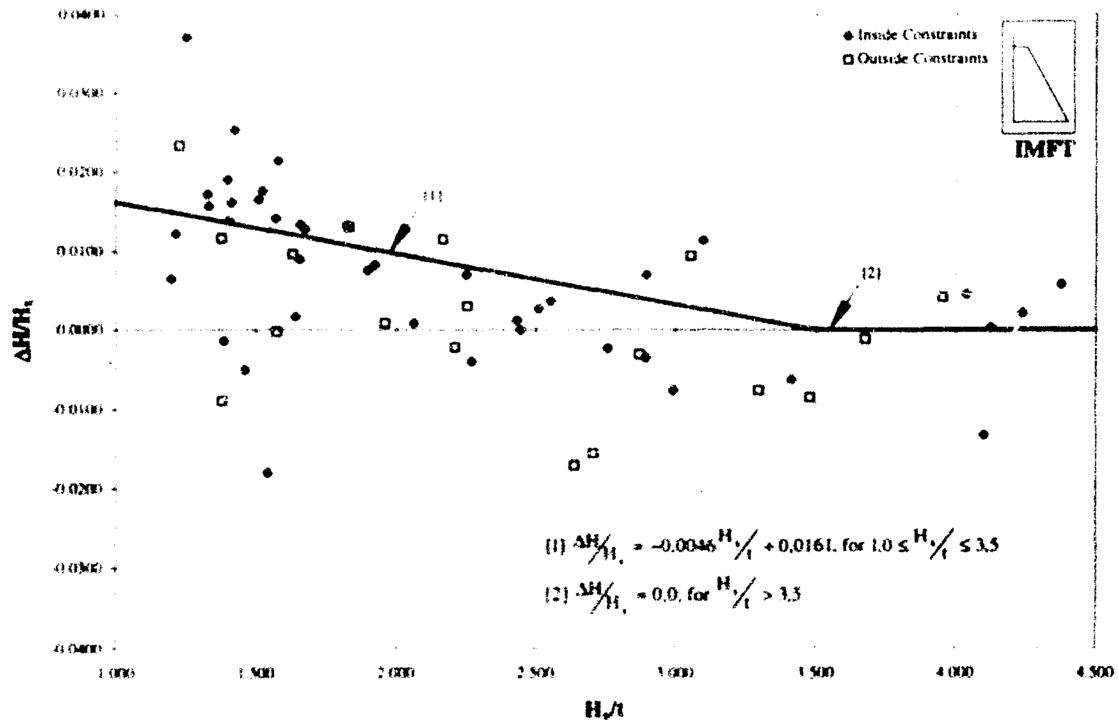
Figure 7.17: *Error in calculated discharge* $\left(Q_{cx}/Q_m\right)$ *expressed as a function of* H_x/t.

The overestimation in flow can be ascribed to the existence of three-dimensional flow conditions just upstream of the weir crest where the low and high notches meet and is most critical when $H_x/_t$ is just greater than one. Energy losses due to this occur downstream of the point of stage measurement. Upstream of the weir crest the water surface rises to compensate for these losses. With increasing stage the higher notch starts to convey more discharge and flow lines near the weir crest tend to become more parallel across the structure, reducing the influence of three-dimensional flow conditions.

For the DWAF formula, the calculated discharges (Q_{cx}) underestimate the actual discharges (Q_m), on average, by 0,3% with a standard deviation of 2,8% for the full data set. For $1{,}0 < H_x/_t < 2{,}0$ the calculated discharges overestimate the actual flows in the same manner as the compound Crump weir without dividing walls. In this region the overestimation of flow reduces as $H_x/_t \rightarrow 2{,}0$. This trend could be ascribed to the reduced influence of three-dimensional flow effects over the weir crest. For $H_x/_t \geq 2{,}0$ the calculated discharges tend to underestimate the actual discharges in general. As flow lines become more parallel the accuracy of the discharge formula should improve; however, the DWAF formula starts to underestimate flows in this region. This can probably be ascribed to an error in the thin-plate discharge formula as used by DWAF. From **Figure 7.17** this underestimation of the actual flow is nearly a constant 2,5%.

Since three-dimensional flow conditions, at the weir ends, result in a raised water surface and thereby an overestimation in total energy head, it is logical to bring in a correction (ΔH) for this error in the total calculated energy head (H_x). Values for ΔH were determined for all the tests by comparing the calculated and measured discharges. Lines were fitted to determine the relationship between the ratio $\Delta H/_{H_x}$ and $H_x/_t$ as shown in **Figure 7.18** for both the IMFT and DWAF formulae.

For the IMFT discharge formula, line [1], in **Figure 7.18**, represents the reducing effect of three-dimensional flow with increasing discharge over the higher notches. The influence of the three-dimensional flow conditions on the total energy head is insignificant when $H_x/_t > 3{,}5$ and therefore $\Delta H/_{H_x} = 0$ as shown in line [2].



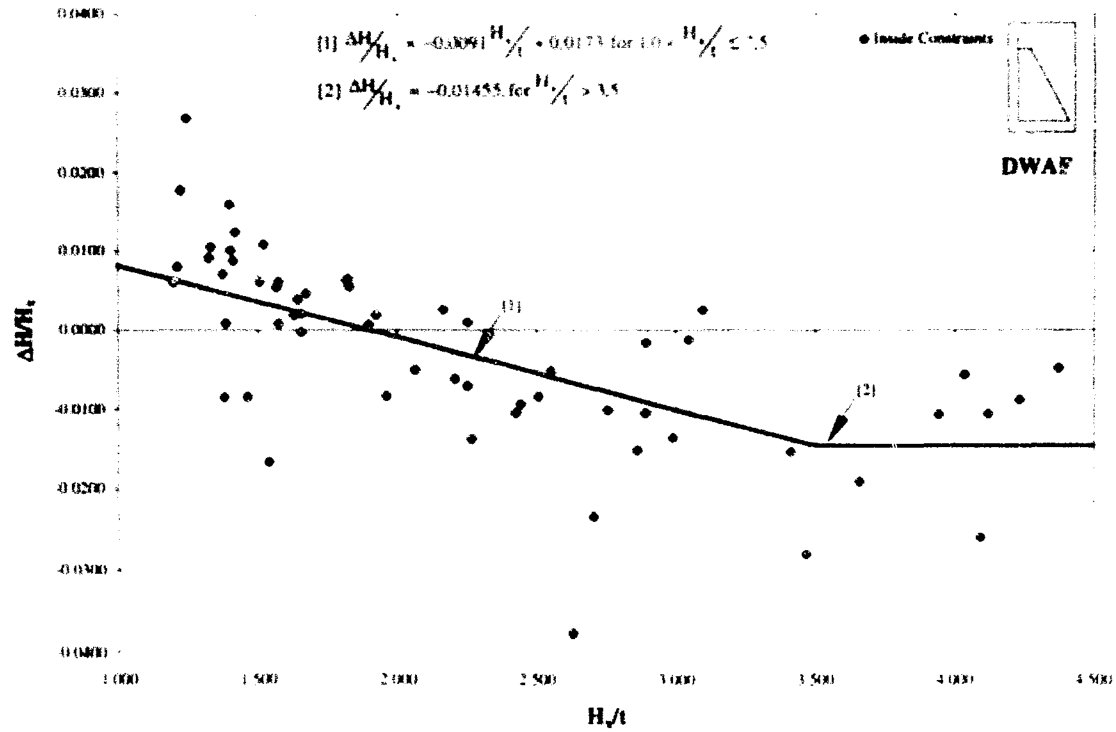


Figure 7.18: *Curves to define the ratio* $\Delta H/H_s$ *expressed as a function of* H_s/t .

A similar pattern of $\Delta H / H_x$ versus H_x / t exists for the DWAF formula; however, the fitted lines are lower and negative values of $\Delta H / H_x$ occur for $H_x / t > 1{,}9$. This is probably due to an inherent error in the DWAF discharge formula resulting in the underestimation of flows calculated over compound thin-plate weirs without dividing walls. For $H_x / t > 3{,}5$ the factor $\Delta H / H_x \approx -0{,}015$, representing those conditions where the flow lines across the weir crest are becoming approximately parallel.

Discharge over a compound thin-plate weir without dividing walls, assuming a horizontal total energy head for the entire weir, is calculated as follows:

$$\left.\begin{array}{ll} Q_{cx} = Q_1 + Q_2 & \text{Total flow} \\ Q_1 = \frac{2}{3}\sqrt{2g}\,C_{d1} l_1 H_x^{1,5} & \text{Low notch flow} \\ Q_2 = \frac{2}{3}\sqrt{2g}\,C_{d2} l_2 (H_x - t)^{1,5} & \text{High notch flow} \end{array}\right\} \quad \text{IMFT}$$

$$\left.\begin{array}{ll} Q_{cx} = Q_1 + Q_2 & \text{Total flow} \\ Q_1 = 1{,}777 C_p l_1 (H_x + 0{,}001)^{1,5} & \text{Low notch flow} \\ Q_2 = 1{,}777 C_p l_1 (H_x - t + 0{,}001)^{1,5} & \text{High notch flow} \end{array}\right\} \quad \text{DWAF}$$

With the improved technique the energy heads to determine flow over the total structure is adjusted as below, in the final iteration of the calculation process.

$$\left.\begin{array}{ll} Q_{\Delta H} = Q_1 + Q_2 & \text{Total flow} \\ Q_1 = \frac{2}{3}\sqrt{2g}\,C_{d1} l_1 (H_x - \Delta H)^{1,5} & \text{Low notch flow} \\ Q_2 = \frac{2}{3}\sqrt{2g}\,C_{d2} l_2 (H_x - t - \Delta H)^{1,5} & \text{High notch flow} \end{array}\right\} \quad \text{IMFT}$$

$$\left.\begin{array}{ll} Q_{\Delta H} = Q_1 + Q_2 & \text{Total flow} \\ Q_1 = 1{,}777 C_p l_1 \left(H_s + 0{,}001 - \Delta H\right)^{1,5} & \text{Low notch flow} \\ Q_2 = 1{,}777 C_p l_1 \left(H_s - t + 0{,}001 - \Delta H\right)^{1,5} & \text{High notch flow} \end{array}\right\} \quad \text{DWAF}$$

Values for ΔH were determined with the formulae as given in **Figure 7.18** to correct for the influence of three-dimensional flow conditions downstream of the point of stage measurement. Discharges were calculated for all the tests for both discharge formulae bringing the correction ΔH to the total energy head into account and are tabulated in **Appendices F3** and **F4** respectively. Examples of the calculation method to determine discharge with the improved method are given in **Appendices E4** and **E6** respectively and shown graphically in **Figure 7.19**. Applying the corrections to the total energy head the error in the calculated discharges reduces considerably for both formulae. On average, the error in the calculated flows for the IMFT formula is 0,0% with a standard deviation of 2,3%. For the DWAF formula the error, on average, is 0,0% with a standard deviation of 2,0%.

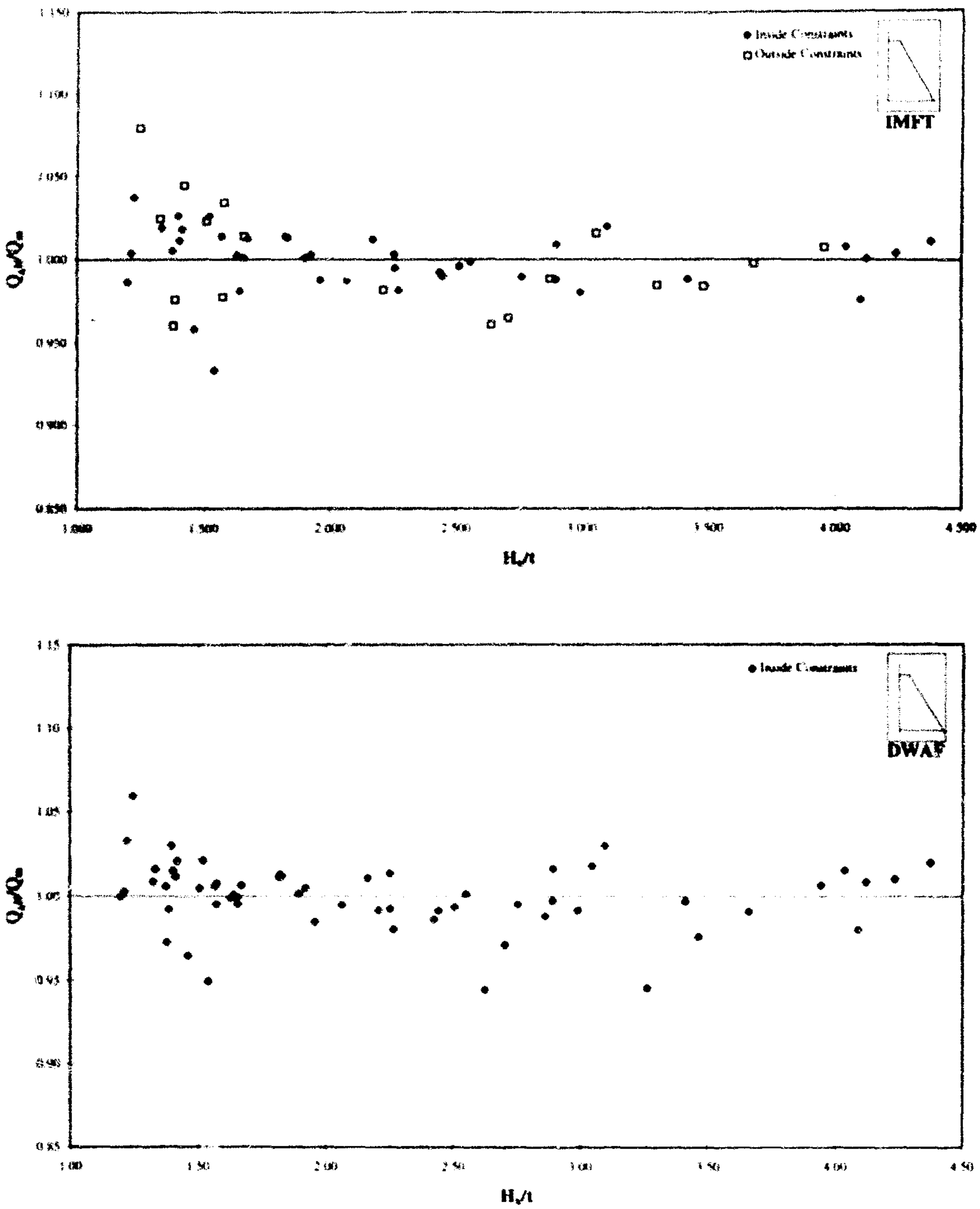


Figure 7.19: *Error in calculated discharge* $\left(Q_{\Delta H}/Q_m\right)$ *expressed as a function of* H_x/t *using the improved calculation technique.*

7.3.4 CONCLUSIONS

Assuming horizontal water levels and total energy heads upstream of the entire width of a Crump compound gauging weir without dividing walls, yields calculated discharges which overestimate actual flows. This overestimation is a result of ignoring the energy losses occurring between the point of stage measurement and the crest of a compound structure, as a result of three-dimensional flow conditions. By compensating for these losses, the effective total energy head in front of the compound weir will be lower than calculated, resulting in lower discharges.

For compound thin-plate weirs with assumed horizontal water levels and total energy heads upstream of the structure, flows determined with the IMFT formula follow a similar pattern as for the Crump weir. Corrections are applied in a similar manner as for the Crump weir. Discharges calculated with the DWAF formula overestimate the actual flows for $H_1/t < 1{,}9$, after which underestimations occur. This difference between the calculated discharges with the IMFT and DWAF formulae indicates a possible error in the DWAF formula.

In this thesis techniques to correct for the three-dimensional flow conditions for both Crump and thin-plate weirs were developed. With these techniques, the total energy head in front of a compound weir is adjusted to compensate for the three-dimensional flow conditions that occur near the weir crests. Ratios to correct for these influences were determined for both Crump and thin-plate weirs. It is recommended that these improved discharge calculation techniques should be applied in the calibration of compound gauging weirs without dividing walls.

8. CONCLUSIONS.

8.1 REQUIRED ACCURACY OF A FLOW RECORD.

A flow record at a gauging weir is assembled in the following two steps; gathering and processing of a stage record, and the derivation of discharge from stage. Errors can occur in either step; however, errors in the derivation of discharge are more controllable due to the technical nature of the calibration process.

Selected flow records were used to determine how sensitive the influence of various assumed error margins in these records were on the required size of a reservoir. For this specific application of a flow record it is clear that an improvement in data quality yields at least an equal reduction in required reservoir capacity. This is especially true for reservoirs designed to yield a large percentage of the MAR. In the design of a reservoir, under South African conditions, **Figures 3.2** to **3.8** may be used to determine an indication of the impact of a potential error in a flow record on the required size.

Guidelines for the required accuracy of a flow record can not be set from this analysis of a single application of data. A broad-based examination of all the applications of the data could lead to the setting of such guidelines.

8.2 CALIBRATION THEORY FOR COMPOUND CRUMP AND THIN-PLATE GAUGING WEIRS OPERATING UNDER MODULAR FLOW CONDITIONS.

As most compound gauging weirs in South Africa are rated in terms of measurements taken at a single point upstream of the lowest notch, these tests were analysed on the same basis to ensure that the results could be applied practically.

8.2.1 COMPOUND WEIRS WITH DIVIDING WALLS.

The standard two-dimensional calibration theory requires the assumption of a horizontal upstream total energy head across the entire width of a compound weir (BSI, 1981). Model tests reveal a consistent underestimation in discharge indicating an inaccuracy in the assumption. In reality, three-dimensional flow conditions exist at the upstream ends of the dividing walls causing energy losses upstream of the point of stage measurement in front of the low notch. When these energy losses are brought into account in the calculation of total energy head in front of the higher notches, with the improved technique described in this thesis, the underestimation in calculated discharge diminishes. With increasing flow depth over the higher notches the influence of three-dimensional flow conditions reduces.

Table 8.1 shows the improvement in the gauging accuracy which is achieved by using the improved calculation technique.

H/t	CRUMP		THIN-PLATE				CALCULATION TECHNIQUE
			IMFT		DWAF		
	AVG	STD	AVG	STD	AVG	STD	
< 1,0	+1,4%	±3,4%	-	-	-	-	STANDARD
> 1,0	-4,3%	±4,8%	-4,9%	±5,7%	-7,8%	±6,1%	STANDARD
< 1,0	+1,4%	±3,4%	-	-	-	-	IMPROVED
> 1,0	0,0%	±2,9%	0,0%	±4,9%	-0,1%	±4,1%	IMPROVED

Table 8.1: *Accuracies in calculated discharge over compound gauging weirs with dividing walls using the standard and improved calibration techniques.*

8.2.2 COMPOUND WEIRS WITHOUT DIVIDING WALLS.

Assuming horizontal upstream water levels and total energy heads result in an overestimation of discharge. In the proximity of the crest three-dimensional flow conditions occur causing energy losses. Measuring stage upstream of these losses leads to an overestimation in total energy head and therefore an overestimation in discharge. By bringing these losses into account for the calculation of total energy head for the entire structure, the improved technique reduces the overestimation in calculated discharge. With increasing flow depth over the higher notches the influence of three-dimensional flow conditions reduces.

Table 8.2 shows the improvement in the gauging accuracy which is achieved by using the improved calculation technique.

Underestimations in discharge, on average, with the standard DWAF formula are in contrast to what is theoretically expected and shown by the IMFT and Crump discharge formulae. This can only be ascribed to an undefined error in the DWAF formula which has been corrected for in the improved calculation technique.

H_1/t	CRUMP		THIN-PLATE				CALCULATION TECHNIQUE
			IMFT		DWAF		
	AVG	STD	AVG	STD	AVG	STD	
< 1,0	+2,7%	±2,4%	-	-	-	-	STANDARD
> 1,0	+2,8%	±2,2%	+1,5%	±2,8%	-0,3%	±2,8%	STANDARD
< 1,0	+0,1%	±2,3%	-	-	-	-	IMPROVED
> 1,0	0,0%	±1,5%	0,0%	±2,3%	0,0%	±2,0%	IMPROVED

Table 8.2: *Accuracies in calculated discharge over compound gauging weirs without dividing walls using the standard and improved calibration techniques.*

Contrary to BSI (1981); the accuracy which is obtainable, with the improved calculation technique, at structures without dividing walls indicate that hydraulic model studies are unnecessary for the calibration of such structures.

8.3 THE NECESSITY FOR THE CONSTRUCTION OF DIVIDING WALLS AT COMPOUND GAUGING WEIRS.

From a South African flow gauging viewpoint the most significant result in this thesis is the accuracy of calibration possible at gauging stations without dividing walls, as shown in **Tables 8.1** and **8.2**. In fact, if more than one notch is operational, structures without dividing walls yield greater accuracy in calculated discharge than structures with dividing walls, for the standard and improved calculation techniques. Contrary to the requirements set by BSI (1981), whereby all compound gauging weirs should be equipped with dividing walls, the results indicate that no improvement in accuracy results from the use of dividing walls.

9. RECOMMENDATIONS.

Based on the conclusions drawn in **Chapter 8**, the following recommendations are made:

- Further comprehensive research over a broad spectrum of the applications of flow records will hopefully result in guidelines to determine the required accuracy of a flow record and the gauging of flow from an economic point of view.

- **Figures 3.2** to **3.8** can be used as indicators of the potential impact of errors in flow records during the planning phase of a reservoir, for South African conditions.

- The improved discharge calculation technique, as described in **Chapter 7**, should be used in the calibration of compound weirs, whilst measuring stage only in front of a single notch.

- Although the DWAF formula, for thin-plate weirs, is not internationally recognised, its broader range of application and equivalent accuracy, when compared to the IMFT formula, indicate that its use within the Department remains justified.

- Whilst dividing walls do not provide any calibration advantages for a compound structure they should be investigated in terms of the additional benefits that arise from their use. This could include the resulting higher approach velocities limiting sedimentation between the walls and thereby limiting the potential for blocked inlet systems.

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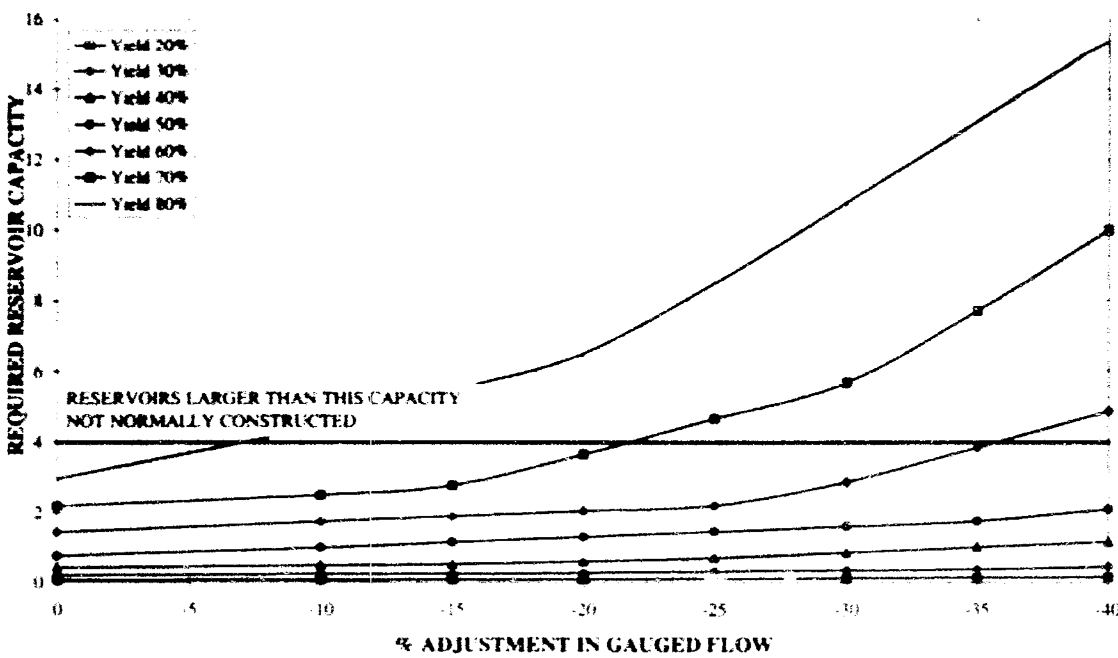
APPENDICES

APPENDIX A

Name of stream	Krokodil River						
Size of catchment in km²	4112						
MAR in m³ • 10⁶	169.52						
Coefficient of variation Cv	0.84						
Gross yield expressed as a percentage of the MAR	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0771	0.0810	0.0926	0.1056	0.1190	0.1321	0.1453	0.1584
30	0.2114	0.2377	0.2527	0.2847	0.3170	0.3492	0.3814	0.4540
40	0.4226	0.4870	0.5193	0.6055	0.7092	0.8620	1.0146	1.1676
50	0.7566	1.0012	1.1543	1.3070	1.4592	1.6146	1.7700	2.1189
60	1.4460	1.7512	1.9069	2.0623	2.2202	2.8832	3.8533	
70	2.1985	2.5094	2.7964	3.6505				
80	2.9607							

\+ Critical period starts at the beginning of the record or ends at the end of the record.

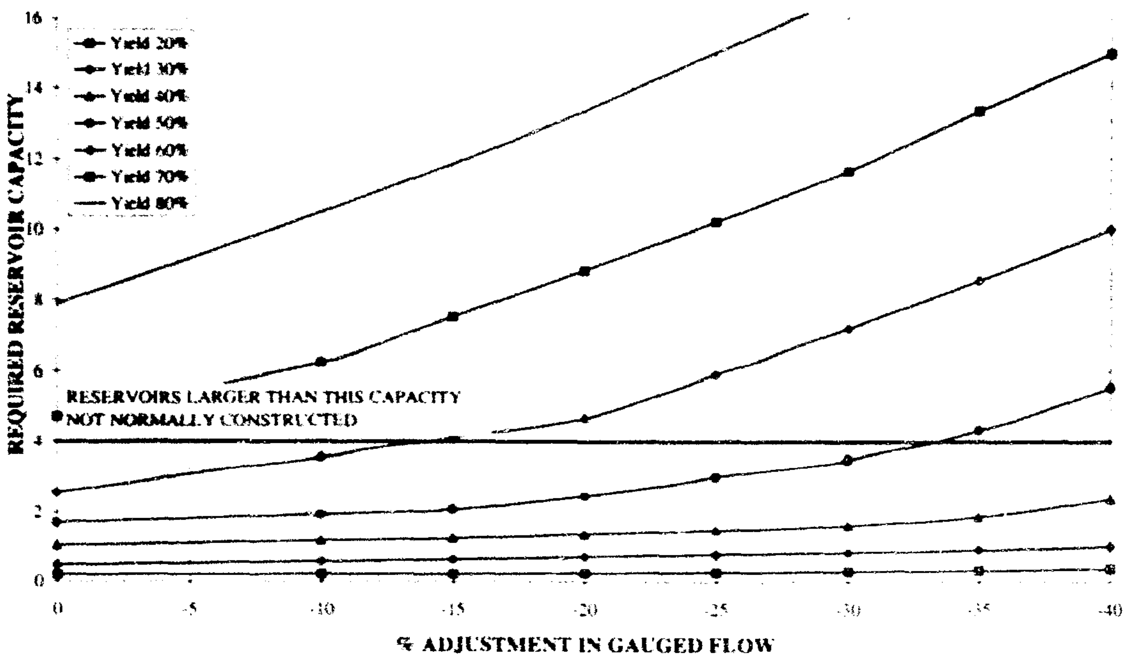
Reservoirs of these capacities are not normally constructed



Name of stream	Hennops River							
Size of catchment in km^2	481							
MAR in m^3 • 10^6	14.21							
Coefficient of variation Cv	1.16							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1985	0.2215	0.2306	0.2449	0.2730	0.3019	0.3314	0.3855
30	0.4775	0.5779	0.6420	0.7166	0.7876	0.8559	0.9249	1.0230
40	1.0469	1.1862	1.2528	1.3659	1.4763	1.6191	1.8842	2.3891
50	1.7067	1.9518	2.0911	2.4744	2.9912	3.5064		
60	2.5747	3.5836						
70								
80								

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

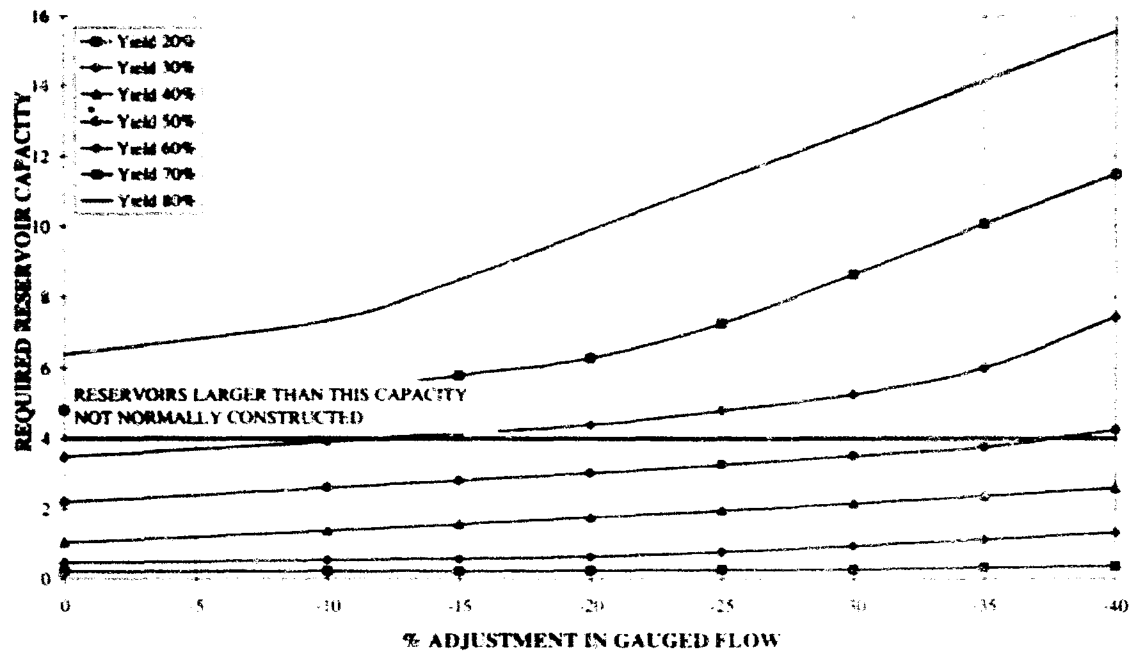


Name of stream	Nzhelele River	
Size of catchment in km²	842	
MAR in $m^3 \cdot 10^6$	46.79	
Coefficient of variation Cv	1.33	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2036	0.2175	0.2292	0.2431	0.2576	0.2736	0.3169	0.3599
30	0.4534	0.5414	0.5844	0.6383	0.7730	0.9346	1.1187	1.3228
40	1.0313	1.3654	1.5587	1.7641	1.9671	2.1716	2.3770	2.6079
50	2.2044	2.6133	2.8170	3.0244	3.2584	3.4943	3.7526	
60	3.4627	3.9116						
70								
80								

\+ Critical period starts at the beginning of the record or ends at the end of the record.

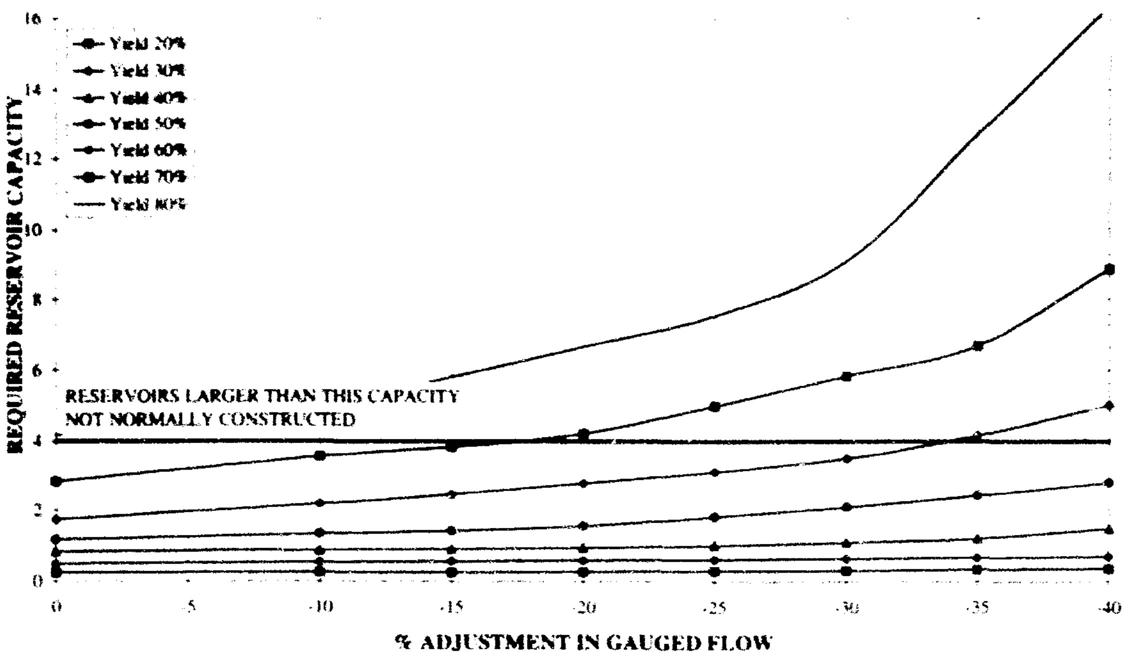
Reservoirs of these capacities are not normally constructed



Name of stream	Olifants River							
Size of catchment in km^2	3627							
MAR in m^3 • 10^6	122.15							
Coefficient of variation Cv	0.97							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2502	0.2569	0.2645	0.2805	0.2961	0.3119	0.3377	0.3644
30	0.4933	0.5464	0.5731	0.5997	0.6262	0.6527	0.6793	0.7060
40	0.8350	0.8881	0.9147	0.9414	1.0207	1.1018	1.2031	1.4619
50	1.1766	1.3372	1.4179	1.5604	1.8270	2.0943	2.4275	2.7887
60	1.7466	2.1933	2.4601	2.7773	3.1187	3.4976		
70	2.8256	3.5665	3.8238					
80								

+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

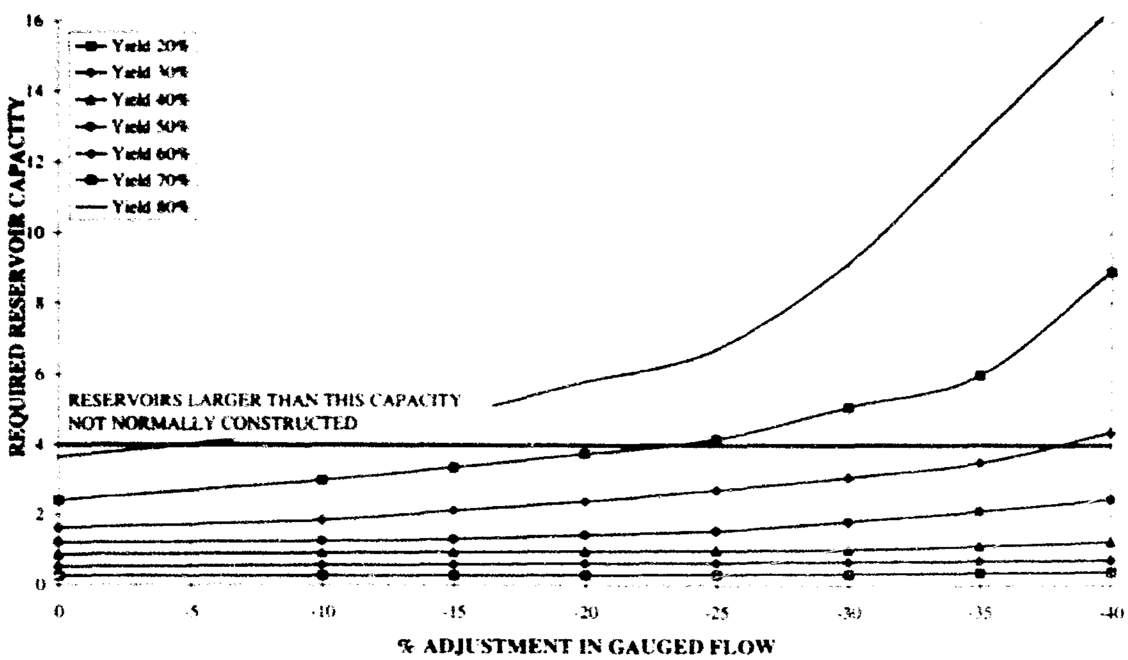


Name of stream	Klein-Olifants River
Size of catchment in km^2	1576
MAR in m^3 • 10^6	53.38
Coefficient of variation Cv	0.96

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2488	0.2654	0.2800	0.2954	0.3102	0.3291	0.3538	0.3791
30	0.5182	0.5686	0.5937	0.6198	0.6450	0.6701	0.6954	0.7207
40	0.8599	0.9103	0.9354	0.9614	0.9867	1.0150	1.1201	1.2404
50	1.2015	1.2519	1.3116	1.4298	1.5510	1.8198	2.1074	2.4556
60	1.6184	1.8612	2.1258	2.4137	2.7278	3.0936	3.5018	
70	2.4335	3.0062	3.3658	3.7451				
80								

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

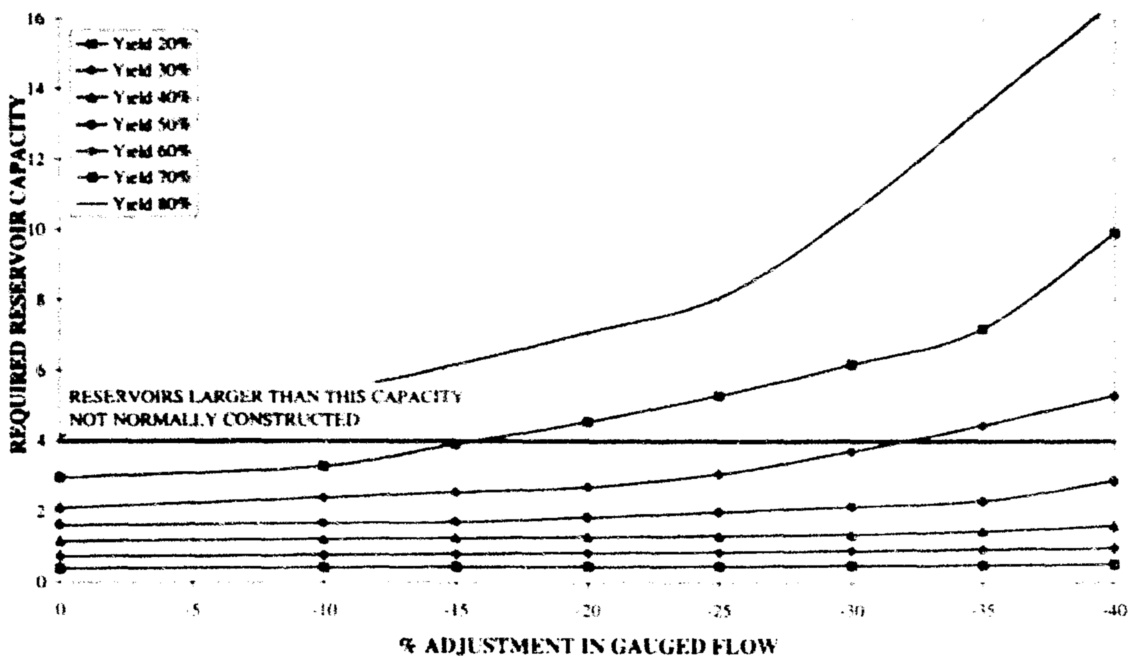


Name of stream	Bronkhorstspruit
Size of catchment in km^2	1263
MAR in m^3 • 10^6	51.67
Coefficient of variation Cv	1.04

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.3885	0.4185	0.4331	0.4470	0.4613	0.4766	0.4919	0.5098
30	0.7300	0.7661	0.8001	0.8329	0.8659	0.9002	0.9352	0.9681
40	1.1561	1.2244	1.2585	1.2912	1.3243	1.3585	1.4565	1.6105
50	1.6144	1.6827	1.7168	1.8588	2.0131	2.1681	2.3231	2.8857
60	2.1079	2.4177	2.5716	2.7254	3.0889	3.7109		
70	2.9745	3.2992	3.9176					
80								

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

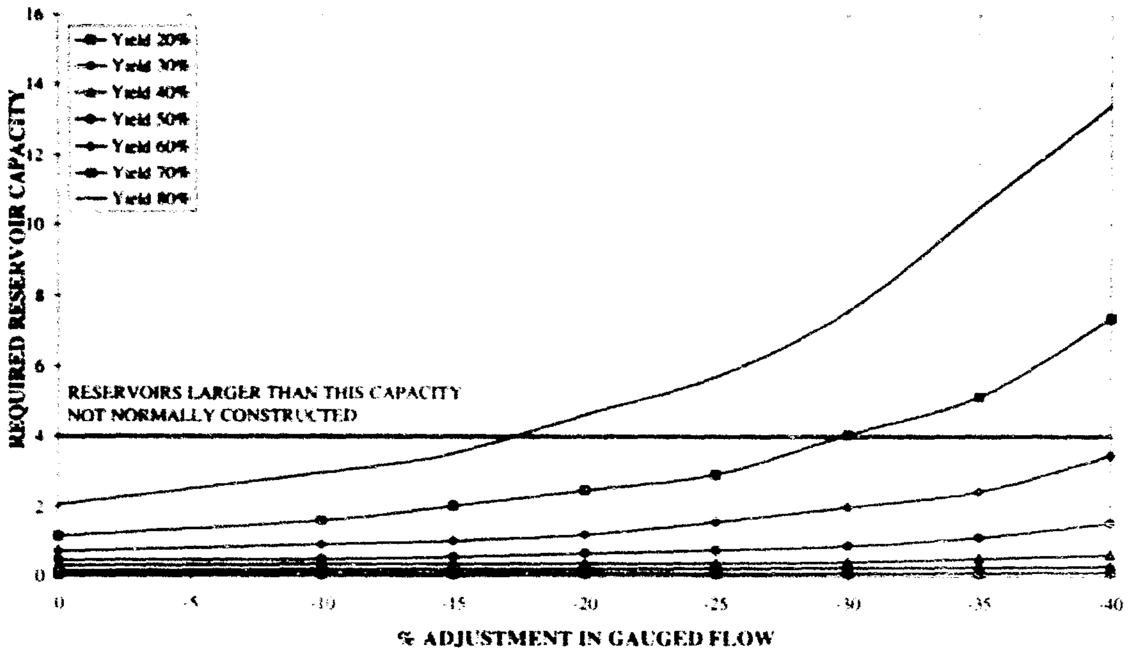


Name of stream	Steelpoort River
Size of catchment in km^2	2240
MAR in $m^3 \cdot 10^6$	121.36
Coefficient of variation Cv	0.76

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0658	0.0724	0.0758	0.0794	0.0826	0.0924	0.1060	0.1211
30	0.1524	0.1819	0.1976	0.2138	0.2302	0.2464	0.2626	0.2791
40	0.3069	0.3397	0.3560	0.3721	0.3885	0.4120	0.5085	0.6078
50	0.4653	0.4980	0.5631	0.6605	0.7595	0.8755	1.1086	1.5260
60	0.7145	0.9114	1.0176	1.2007	1.5653	2.0075	2.4506	3.4587
70	1.1630	1.6172	2.0477	2.4907	2.9348			
80	2.0879	2.9721	3.5122					

\+ Critical period starts at the beginning of the record or ends at the end of the record.

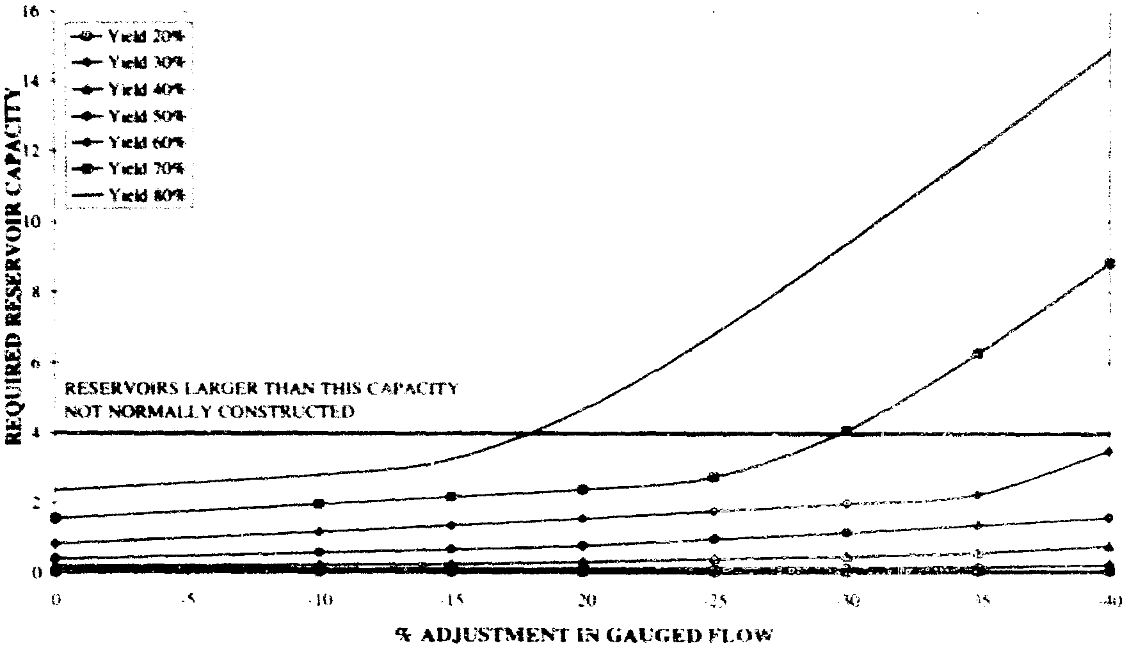
Reservoirs of these capacities are not normally constructed



Name of stream	Dorps River							
Size of catchment in km²	701							
MAR in $m^3 \cdot 10^6$	69.52							
Coefficient of variation Cv	0.73							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0328	0.0379	0.0434	0.0497	0.0559	0.0621	0.0693	0.0766
30	0.1000	0.1151	0.1225	0.1300	0.1475	0.1658	0.1857	0.2450
40	0.1965	0.2346	0.2549	0.3275	0.4147	0.5024	0.5939	0.7811
50	0.4090	0.5849	0.6728	0.7895	0.9762	1.1636	1.3750	1.5955
60	0.8432	1.1725	1.3601	1.5620	1.7818	2.0028	2.2704	3.4933
70	1.5552	1.9692	2.1904	2.4119	2.7586			
80	2.3768	2.8191	3.2514	[illegible]				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

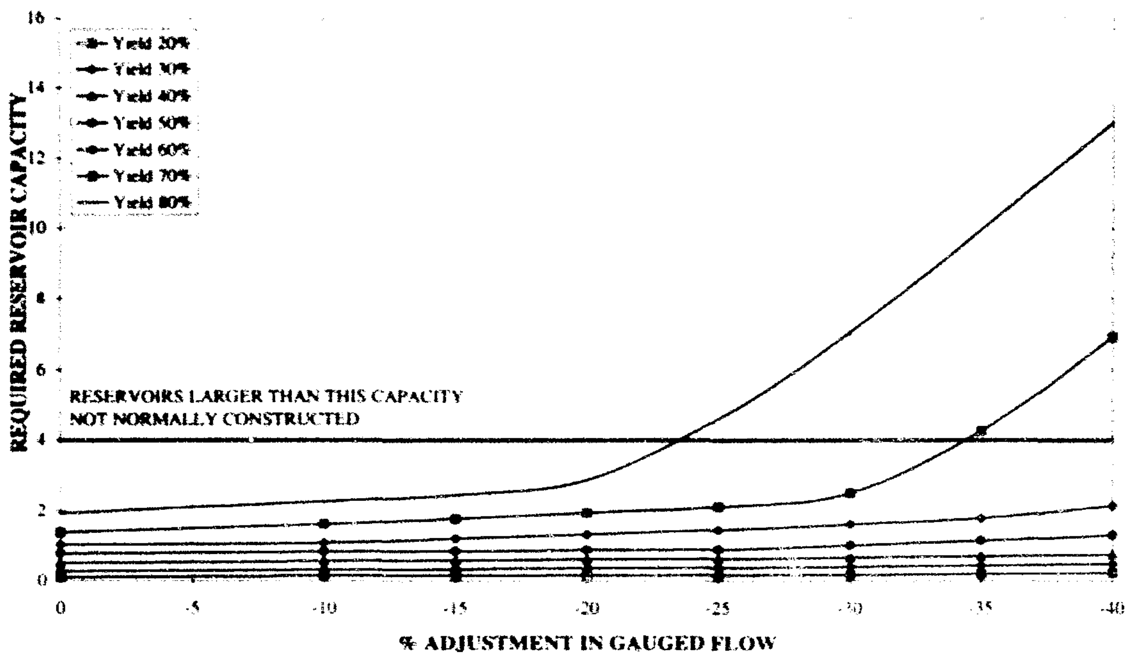
Reservoirs of these capacities are not normally constructed



Name of stream	Vaal River							
Size of catchment in km^2	38505							
MAR in m^3 • 10^6	1637.86							
Coefficient of variation Cv	0.56							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1083	0.1308	0.1420	0.1533	0.1645	0.1758	0.1870	0.2074
30	0.2749	0.3110	0.3354	0.3598	0.3842	0.4086	0.4329	0.4591
40	0.5123	0.5610	0.5858	0.6121	0.6384	0.6647	0.6910	0.7184
50	0.7651	0.8177	0.8441	0.8704	0.8980	1.0215	1.1449	1.2977
60	1.0234	1.0776	1.2011	1.3246	1.4533	1.6264	1.7995	2.1602
70	1.3807	1.6276	1.7821	1.9552	2.1283	2.5201		
80	1.9378	2.2840	2.4571	2.8803				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

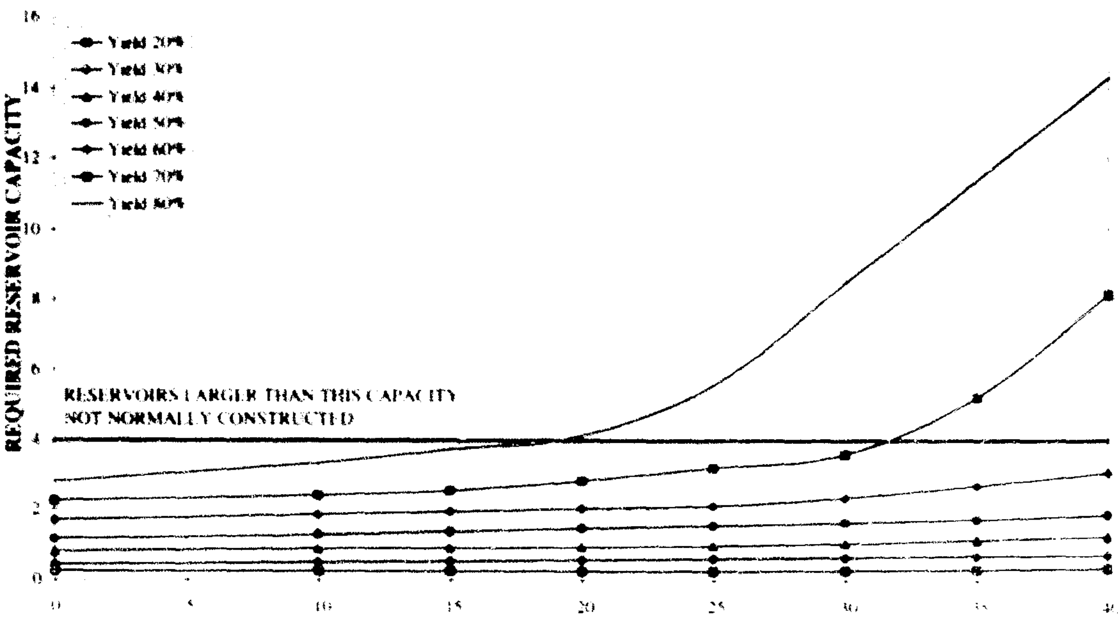


Name of stream	Vaal River
Size of catchment in km^2	7924
MAR in m^3 • 10^6	495.45
Coefficient of variation Cv	0.76

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2544	0.2640	0.2687	0.2735	0.2783	0.2885	0.3137	0.3448
30	0.4551	0.5171	0.5481	0.5791	0.6100	0.6410	0.6721	0.7041
40	0.8134	0.8754	0.9064	0.9387	0.9865	1.0697	1.1527	1.2359
50	1.1734	1.2956	1.3787	1.4617	1.5448	1.6280	1.7110	1.8602
60	1.6876	1.8539	1.9370	2.0200	2.1031	2.3478	2.7039	3.0882
70	2.2459	2.4122	2.5463	2.8355	3.2183	3.6028	[illegible]	[illegible]
80	2.8042	3.3490	3.7332	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

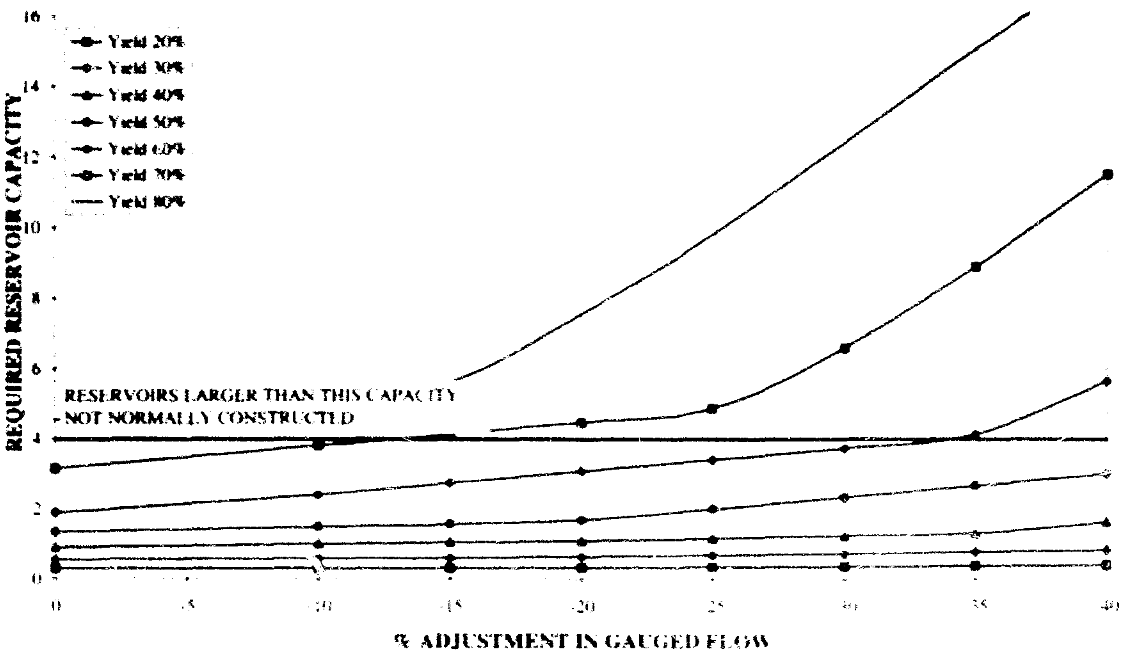


Name of stream	Harts River	
Size of catchment in km^2	2919	
MAR in m^3 • 10^6	26.29	
Coefficient of variation Cv	1.48	

Gross yield expressed as a percentage of the MAR	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.303+	0.305+	0.3160	0.3316	0.3434	0.3564	0.3731	0.3845
30	0.5503	0.5781	0.5910	0.6329	0.6755	0.7197	0.7672	0.8098
40	0.9015	0.9924	1.0354	1.0829	1.1494	1.2232	1.2985	1.6130
50	1.3515	1.4916	1.5651	1.6908	2.0191	2.3443	2.6722	2.9963
60	1.9092	2.4214	2.7485	3.0741	3.4024	3.7276		
70	3.1519	3.8047						
80								

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

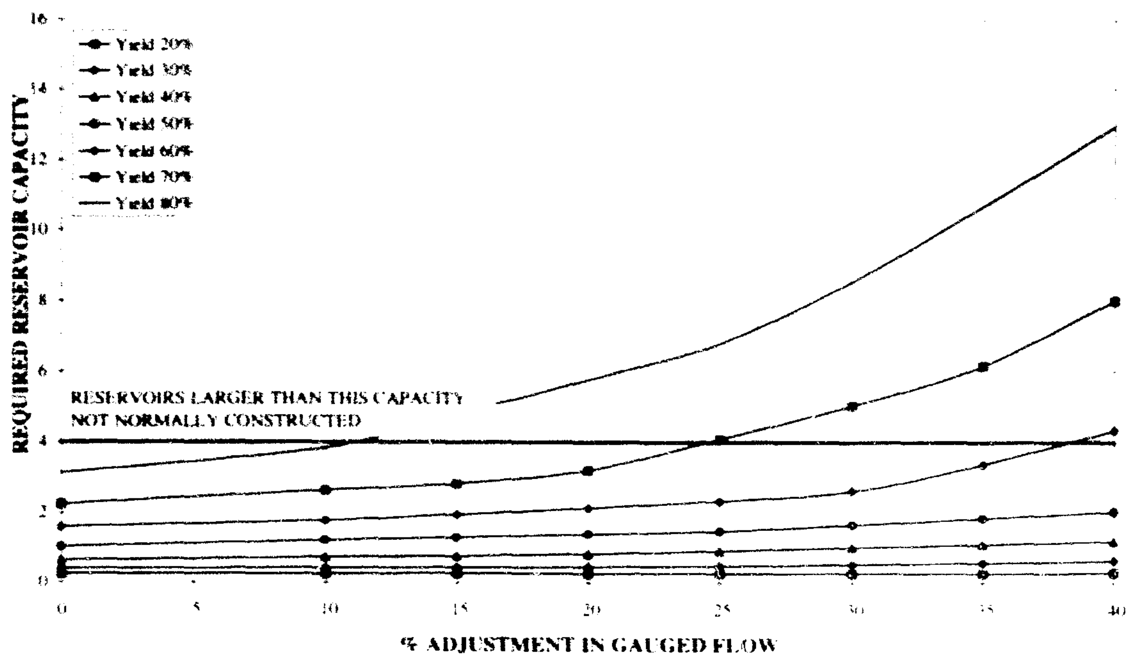


Name of stream	Sand River
Size of catchment in km²	3665
MAR in $m^3 \bullet 10^6$	111.67
Coefficient of variation Cv	1.11

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2353	0.2434	0.2475	0.2515	0.2557	0.2596	0.2636	0.2724
30	0.3937	0.4088	0.4291	0.4497	0.4727	0.5142	0.5579	0.6121
40	0.6303	0.7144	0.7581	0.8165	0.9093	1.0021	1.0947	1.1871
50	1.0207	1.2059	1.2985	1.3915	1.4843	1.6647	1.8552	2.0457
60	1.5956	1.7808	1.9594	2.1500	2.3409	2.6037	3.3601	
70	2.2544	2.6354	2.8261	3.2031				
80	3.1210	3.8347	[illegible]	[illegible]				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

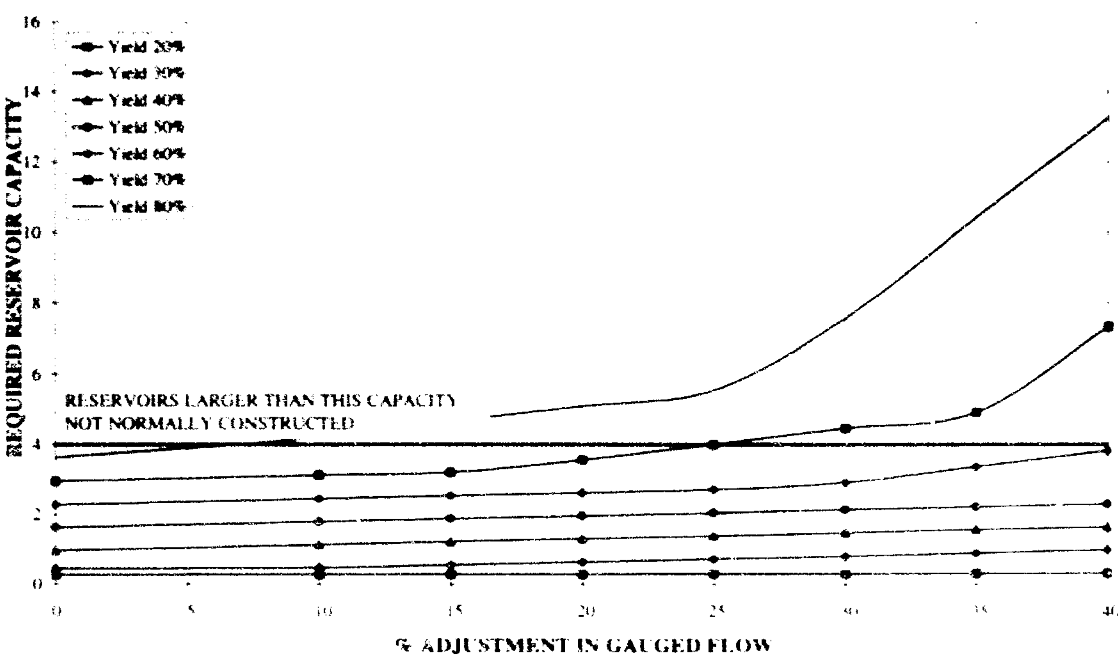


Name of stream	Vet River
Size of catchment in km^2	4750
MAR in m^3 • 10^6	152.81
Coefficient of variation Cv	1.00

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2605	0.2710	0.2763	0.2818	0.2871	0.2922	0.2976	0.3113
30	0.4438	0.4670	0.5506	0.6346	0.7180	0.8022	0.8869	0.9725
40	0.9578	1.1254	1.2109	1.2968	1.3820	1.4679	1.5535	1.6391
50	1.6209	1.7920	1.8775	1.9634	2.0486	2.1346	2.2202	2.3058
60	2.2875	2.4586	2.5442	2.6300	2.7152	2.9131	3.3659	3.8174
70	2.9542	3.1253	3.2108	3.5498				
80	3.6208							

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

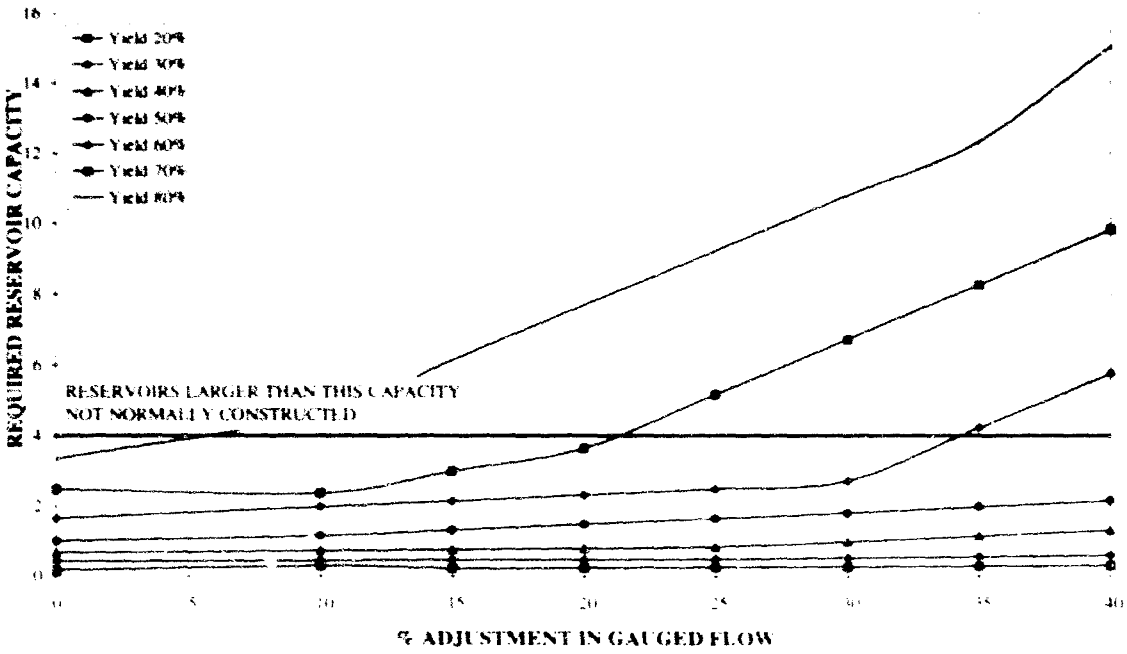


Name of stream	Renoster River						
Size of catchment in km^2	2147						
MAR in m^3 • 10^6	79.53						
Coefficient of variation Cv	0.90						

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1797	0.2898	0.2252	0.2400	0.2553	0.2706	0.2858	0.3012
30	0.4213	0.4515	0.4668	0.4817	0.4970	0.5246	0.5621	0.5998
40	0.6630	0.7245	0.7622	0.7990	0.8370	0.9884	1.1584	1.3279
50	0.9995	1.1516	1.3206	1.4911	1.6604	1.8301	2.0001	2.1696
60	1.6536	1.9932	2.1622	2.3327	2.5021	2.7288		
70	2.4952	2.3848	3.0038	3.632+				
80	3.3369	[illegible]	[illegible]	[illegible]				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

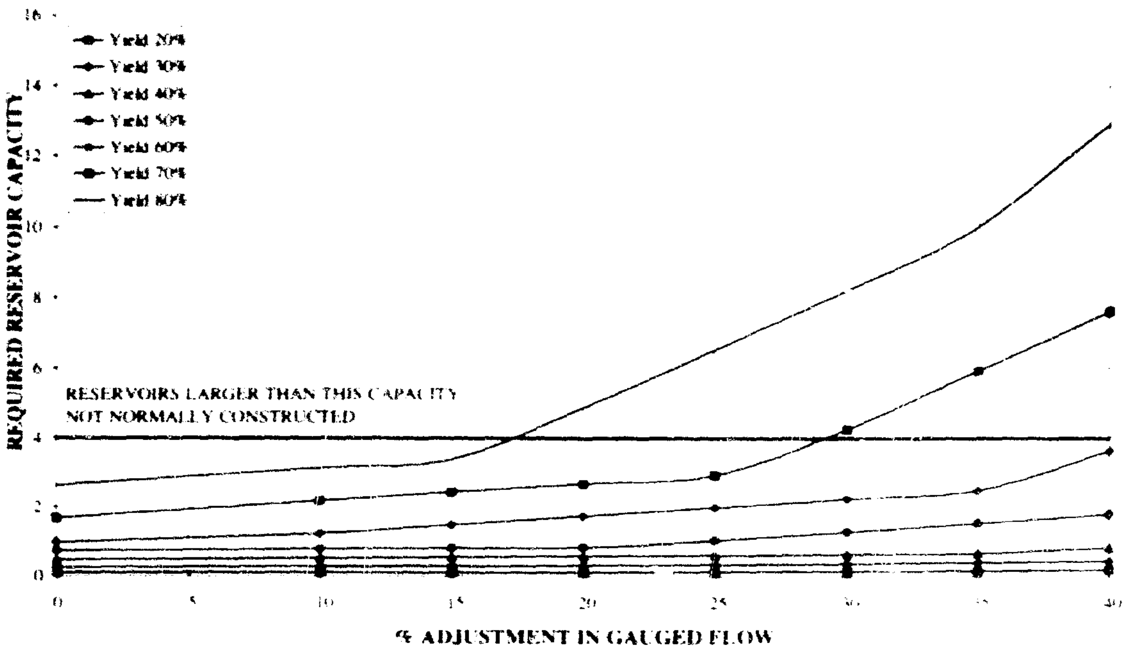
Reservoirs of these capacities are not normally constructed



Name of stream	Wilge river							
Size of catchment in km²	15673							
MAR in $m^3 \cdot 10^6$	678.80							
Coefficient of variation Cv	0.76							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1045	0.1119	0.1159	0.1295	0.1433	0.1571	0.1709	0.1847
30	0.2494	0.2770	0.2907	0.3191	0.3476	0.3761	0.4046	0.4331
40	0.4634	0.5204	0.5489	0.5774	0.6059	0.6344	0.6629	0.8195
50	0.7218	0.7788	0.8073	0.8357	1.0243	1.2755	1.5267	1.7778
60	0.9801	1.2294	1.4804	1.7316	1.9826	2.2338	2.4850	3.637+
70	1.6853	2.1876	2.4387	2.6899	2.9409			
80	2.6436	3.1459	3.3970	4.[illegible]+				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

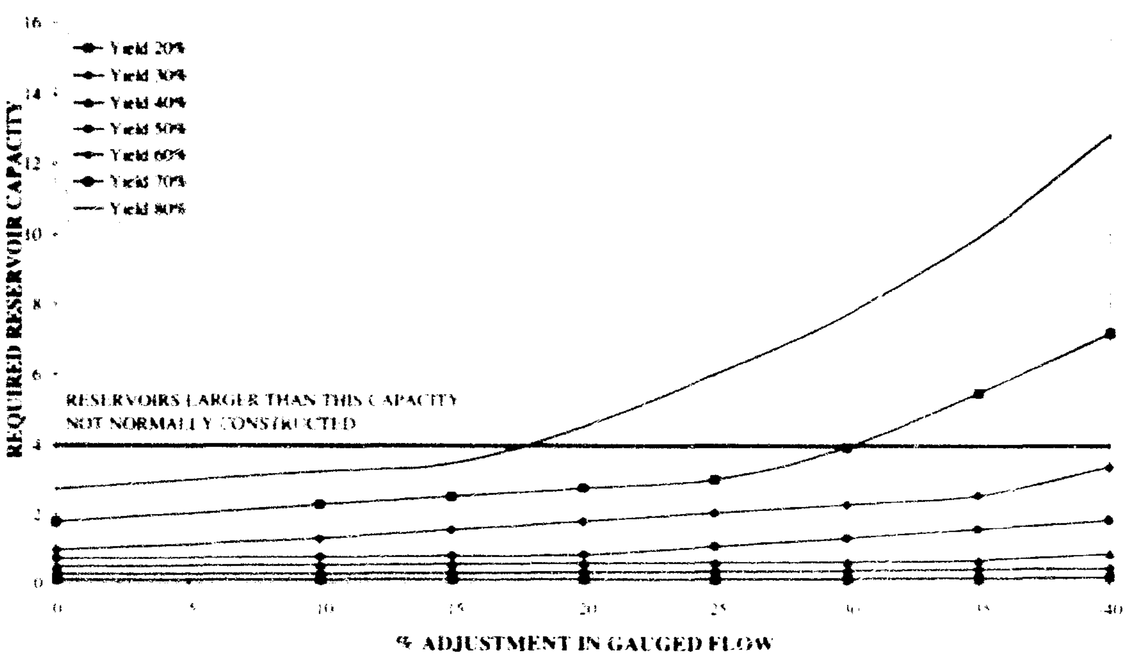


Name of stream	Liebenbergvlei	
Size of catchment in km^2	742	
MAR in m^3 • 10^6	34.30	
Coefficient of variation Cv	0.79	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1058	0.1134	0.1211	0.1348	0.1482	0.1616	0.1751	0.1888
30	0.2559	0.2824	0.3006	0.3304	0.3578	0.3846	0.4129	0.4406
40	0.4764	0.5318	0.5589	0.5887	0.6161	0.6429	0.6712	0.8874
50	0.7348	0.7902	0.8173	0.8623	1.1081	1.3533	1.5991	1.8457
60	0.9931	1.3299	1.5760	1.8206	2.0664	2.3116	2.5574	3.388+
70	1.7982	2.2882	2.5343	2.7789	3.0247	3.953+	[illegible]	[illegible]
80	2.7564	3.2465	3.4926	4.519+	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

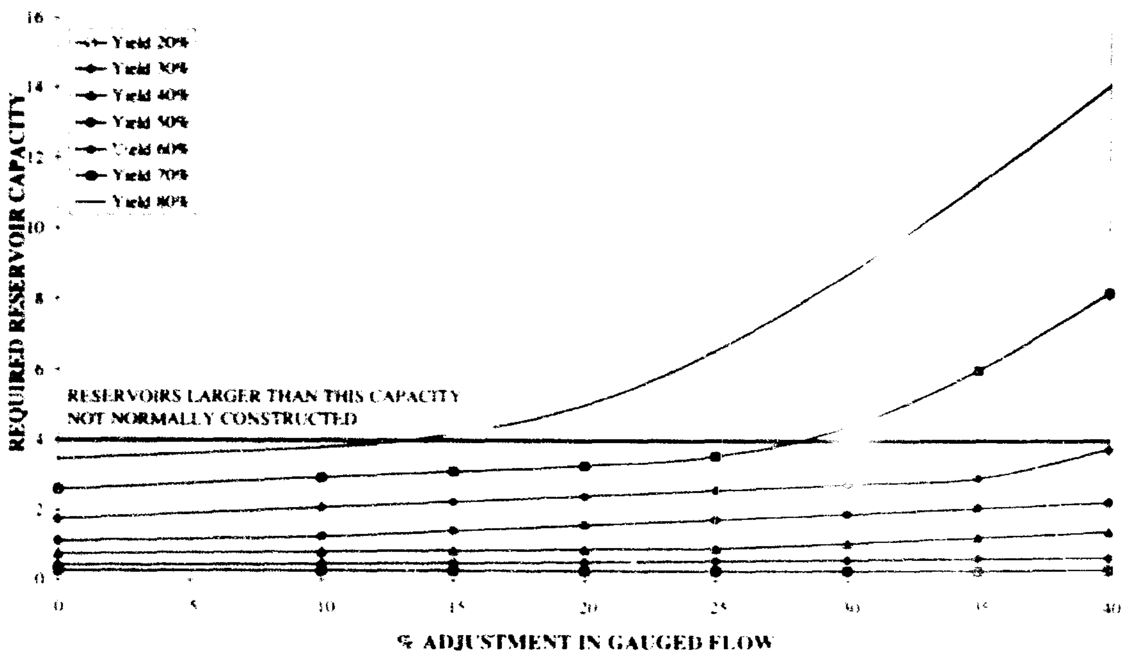


Name of stream	Vaal River
Size of catchment in km^2	107911
MAR in m^3 • 10^6	44.20
Coefficient of variation Cv	1.08

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2610	0.2667	0.2694	0.2723	0.2750	0.2775	0.2810	0.3054
30	0.4193	0.4574	0.4909	0.5239	0.5567	0.5901	0.6247	0.6591
40	0.7423	0.8091	0.8441	0.8790	0.9136	1.0607	1.2297	1.3947
50	1.0986	1.2437	1.4102	1.5772	1.7449	1.9107	2.0797	2.2446
60	1.7595	2.0937	2.2602	2.4272	2.5948	2.7607	2.9345	3.7463
70	2.6095	2.9437	3.1102	3.2771	3.5525			
80	3.4595	3.7936	[illegible]	[illegible]				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

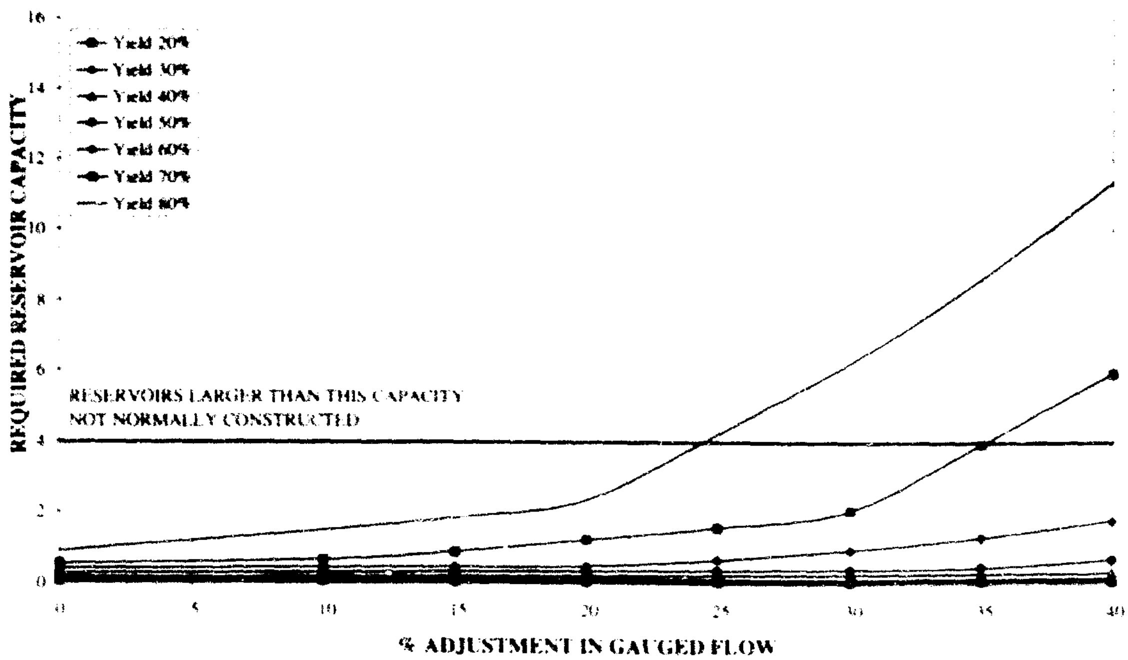
Reservoirs of these capacities are not normally constructed



Name of stream	Oranje River							
Size of catchment in km²	24550							
MAR in $m^3 \cdot 10^6$	2879.93							
Coefficient of variation Cv	0.35							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0677	0.0710	0.0726	0.0742	0.0758	0.0774	0.0790	0.0806
30	0.1177	0.1209	0.1226	0.1242	0.1258	0.1285	0.1489	0.1701
40	0.1677	0.1843	0.2056	0.2268	0.2480	0.2693	0.2905	0.3118
50	0.2835	0.3260	0.3472	0.3685	0.3897	0.4109	0.4702	0.6852
60	0.4252	0.4676	0.4889	0.5101	0.6906	0.9591	1.3013	1.7499
70	0.5668	0.7004	0.9110	1.2330	1.5752	2.0415	3.940+	
80	0.9208	1.5069	1.8491	2.3333				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

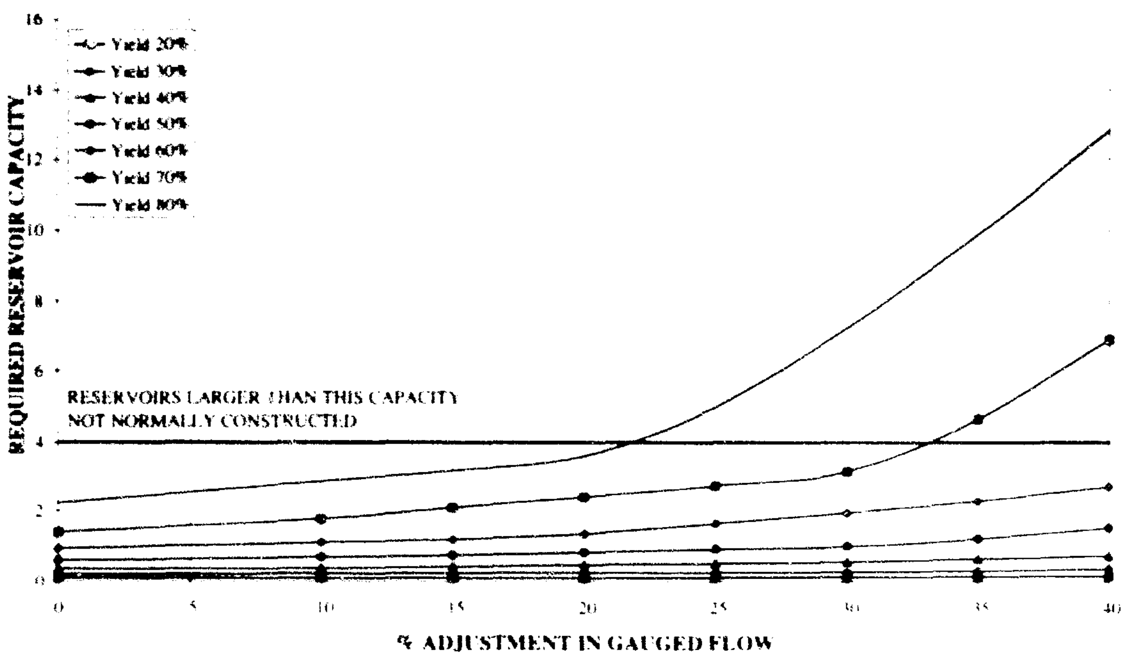
Reservoirs of these capacities are not normally constructed



Name of stream	Caledon River							
Size of catchment in km^2	15245							
MAR in $m^3 \bullet 10^6$	1159.38							
Coefficient of variation Cv	0.62							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1047	0.1076	0.1090	0.1115	0.1232	0.1350	0.1472	0.1603
30	0.2143	0.2404	0.2534	0.2665	0.2794	0.2925	0.3199	0.3703
40	0.3727	0.3987	0.4433	0.4937	0.5441	0.5945	0.6682	0.7553
50	0.6172	0.7179	0.7699	0.8570	0.9440	1.0311	1.2396	1.5512
60	0.9588	1.1329	1.2199	1.3858	1.6744	1.9862	2.2979	2.6949
70	1.4088	1.7977	2.1093	2.4211	2.7326	3.1440		
80	2.2327	2.8560	3.1676	3.5931				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

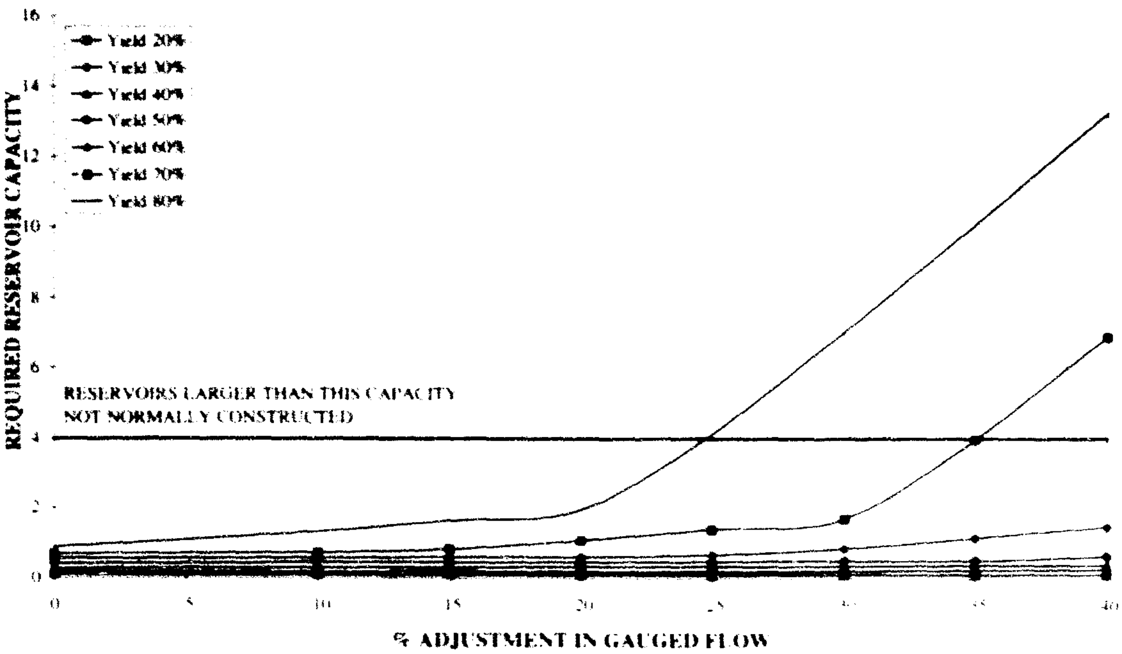


Name of stream	Oranje River	
Size of catchment in km²	70749	
MAR in m³ • 10⁶	3539.31	
Coefficient of variation Cv	0.35	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1014	0.1036	0.1052	0.1069	0.1089	0.1116	0.1144	0.1171
30	0.1702	0.1757	0.1841	0.1983	0.2124	0.2266	0.2408	0.2549
40	0.2833	0.3116	0.3258	0.3399	0.3541	0.3683	0.3824	0.3966
50	0.4249	0.4533	0.4674	0.4816	0.4958	0.5099	0.5241	0.6308
60	0.5666	0.5949	0.6091	0.6233	0.6811	0.8595	1.1509	1.4547
70	0.7082	0.7473	0.8419	1.0896	1.3934	1.6971	3.967+	
80	0.9081	1.3321	1.6358	1.9396				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

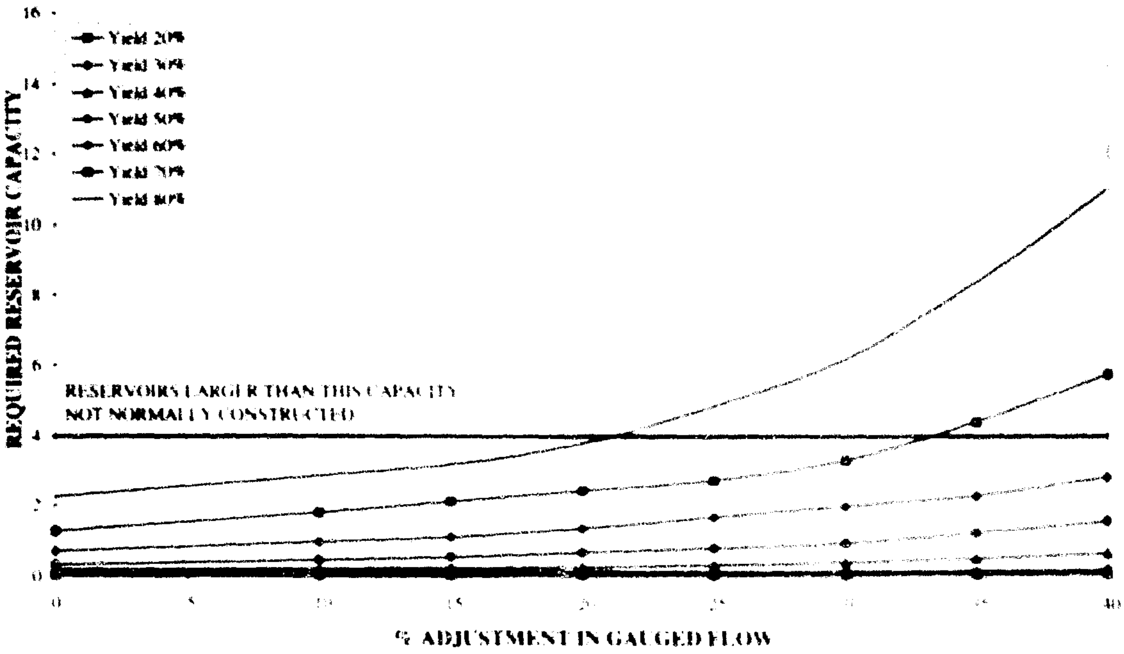
Reservoirs of these capacities are not normally constructed



Name of stream	Olifants River							
Size of catchment in km^2	2033							
MAR in m^3 • 10^6	407.09							
Coefficient of variation Cv	0.49							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0745	0.0765	0.0778	0.0810	0.0842	0.0875	0.0916	0.0961
30	0.1351	0.1441	0.1486	0.1531	0.1576	0.1621	0.1813	0.2077
40	0.2101	0.2242	0.2506	0.2770	0.3419	0.4146	0.5290	0.6601
50	0.3463	0.4821	0.5631	0.6941	0.8252	0.9562	1.2497	1.5638
60	0.7281	0.9904	1.1214	1.3740	1.6879	2.0021	2.3163	2.8437
70	1.2864	1.8126	2.1265	2.4406	2.7546	3.3175		
80	2.2508	2.8792	3.1993	3.7915				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

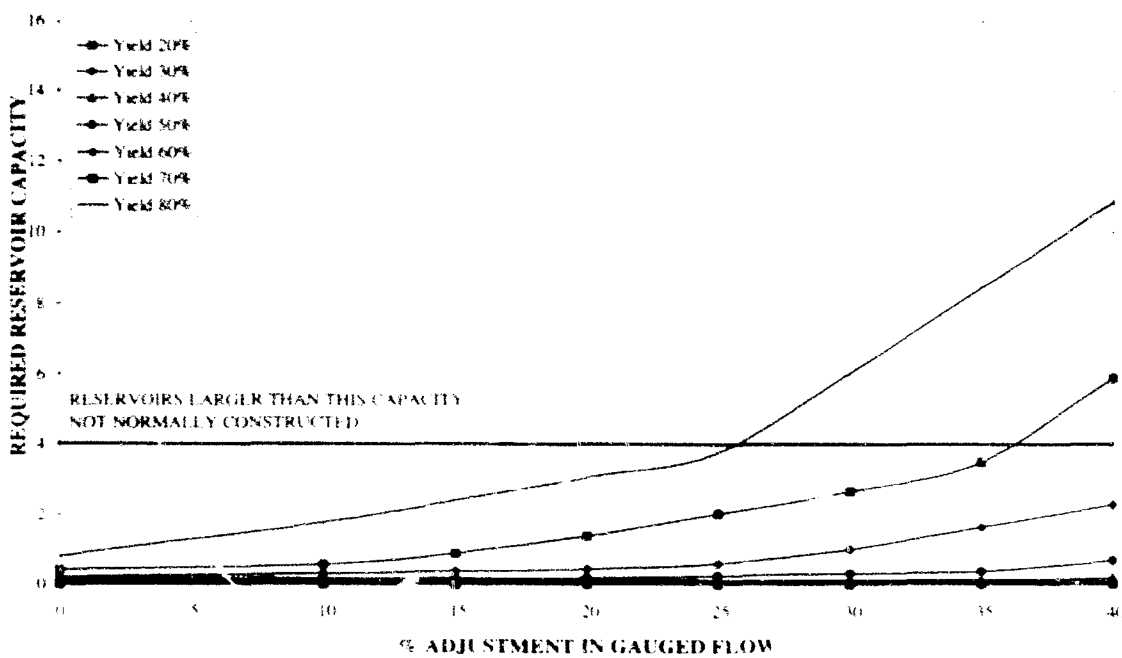


Name of stream	Koekedou River
Size of catchment in km^2	49.8
MAR in $m^3 \cdot 10^6$	27.89
Coefficient of variation Cv	0.33

Gross yield expressed as a percentage of the MAR	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0000	0.0007	[illegible]	0.0093	0.0154	0.0204	0.0269	0.0319
30	0.0371	0.0482	0.0546	0.0593	0.0654	0.0728	0.0817	0.0910
40	0.0878	0.1028	0.1118	0.1207	0.1293	0.1390	0.1483	0.2022
50	0.1512	0.1695	0.1784	0.1874	0.2510	0.3195	0.3870	0.6894
60	0.2178	0.3031	0.3691	0.4370	0.5939	1.0057	1.6514	2.2897
70	0.4201	0.5555	0.8889	1.3876	2.0276	2.6723	3.488+	[illegible]
80	0.7973	1.7724	2.4128	3.0542	3.7388	[illegible]	[illegible]	[illegible]

Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

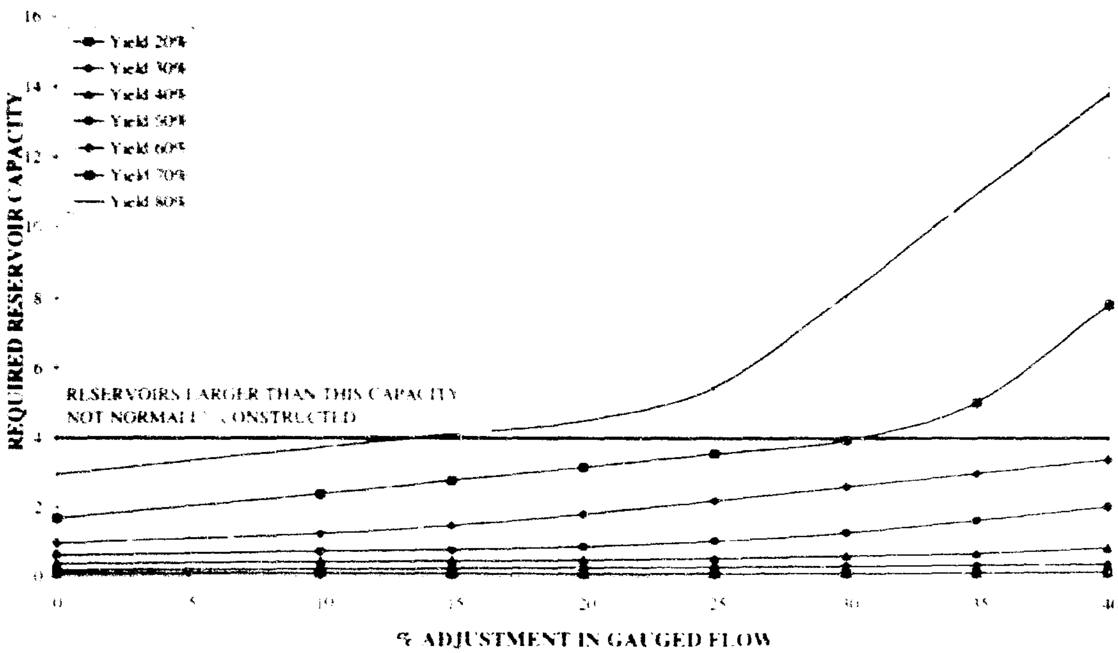


Name of stream	Moordkuil River	
Size of catchment in km²	215	
MAR in m³ • 10⁶	32.52	
Coefficient of variation Cv	0.71	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0871	0.0905	0.0914	0.0940	0.1037	0.1146	0.1294	0.1438
30	0.1872	0.2167	0.2405	0.2660	0.2918	0.3167	0.3423	0.3767
40	0.3889	0.4409	0.4655	0.5019	0.5548	0.6105	0.6857	0.8400
50	0.6280	0.7355	0.7907	0.8812	1.0475	1.2869	1.6492	2.0385
60	0.9824	1.2577	1.4953	1.8278	2.2109	2.5990	2.9825	3.3718
70	1.7057	2.3868	2.7739	3.1611	3.5442	3.9323	[illegible]	[illegible]
80	2.9510	3.7201	**4.1072**	**4.4943**	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

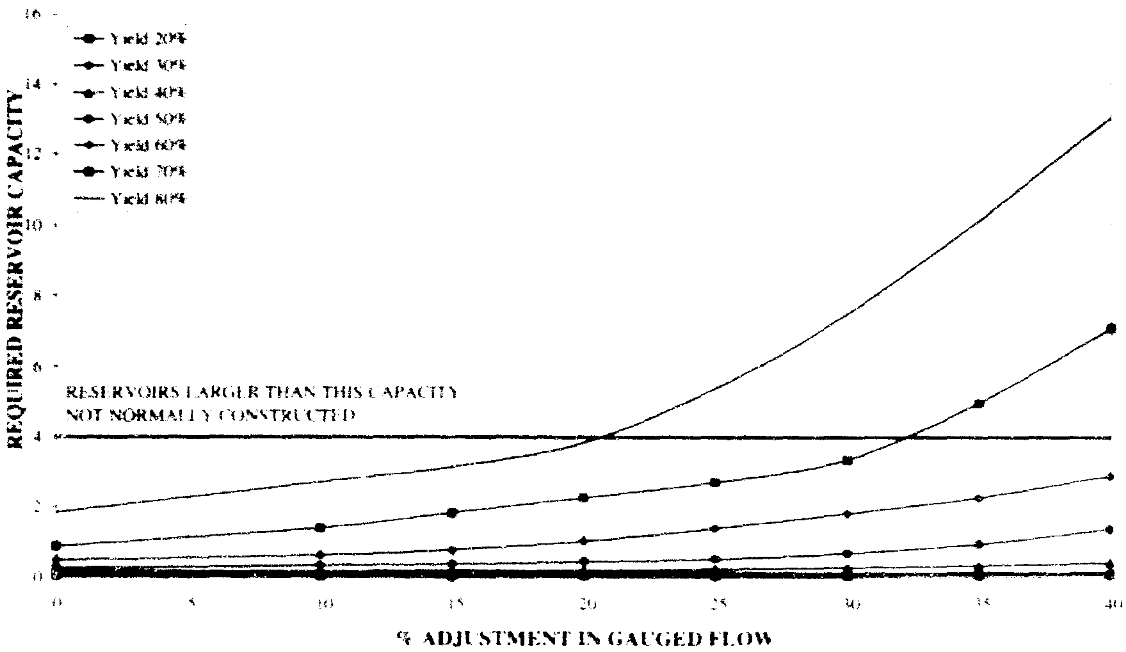
Reservoirs of these capacities are not normally constructed



Name of stream Size of catchment in km^2 MAR in m^3 • 10^6 Coefficient of variation Cv	Groot Brak River 131 38.30 0.53							[illegible]
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	−10%	−15%	−20%	−25%	−30%	−35%	−40%
20	0.0582	0.0637	0.0668	0.0699	0.0728	0.0757	0.0785	0.0817
30	0.1165	0.1220	0.1251	0.1283	0.1311	0.1340	0.1407	0.1587
40	0.1748	0.1803	0.1921	0.2121	0.2498	0.2934	0.3477	0.4227
50	0.2646	0.3448	0.3884	0.4524	0.5292	0.6914	0.9400	1.3739
60	0.4844	0.6361	0.7819	1.0234	1.3877	1.8214	2.2599	2.8828
70	0.8738	1.4027	1.8364	2.2728	2.7088	3.3620	[illegible]	[illegible]
80	1.8512	2.7212	3.1586	3.8440	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

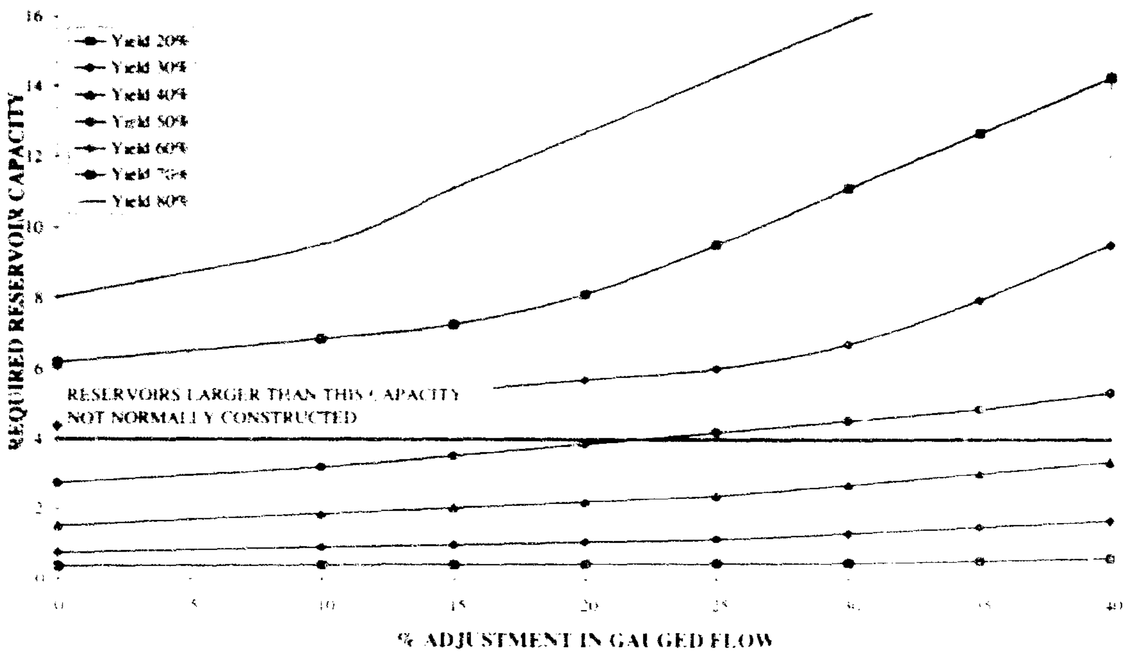
Reservoirs of these capacities are not normally constructed



Name of stream	Buffalo River							
Size of catchment in km^2	913							
MAR in m^3 • 10^6	44.57							
Coefficient of variation Cv	1.32							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.3574	0.3915	0.4078	0.4265	0.4431	0.4599	0.5155	0.5921
30	0.7342	0.8887	0.9682	1.0485	1.1277	1.2937	1.4741	1.6515
40	1.5042	1.8452	2.0234	2.2033	2.3817	2.6951	3.0220	3.3487
50	2.7540	3.2061	3.5313	3.8595				
60								
70								
80								

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

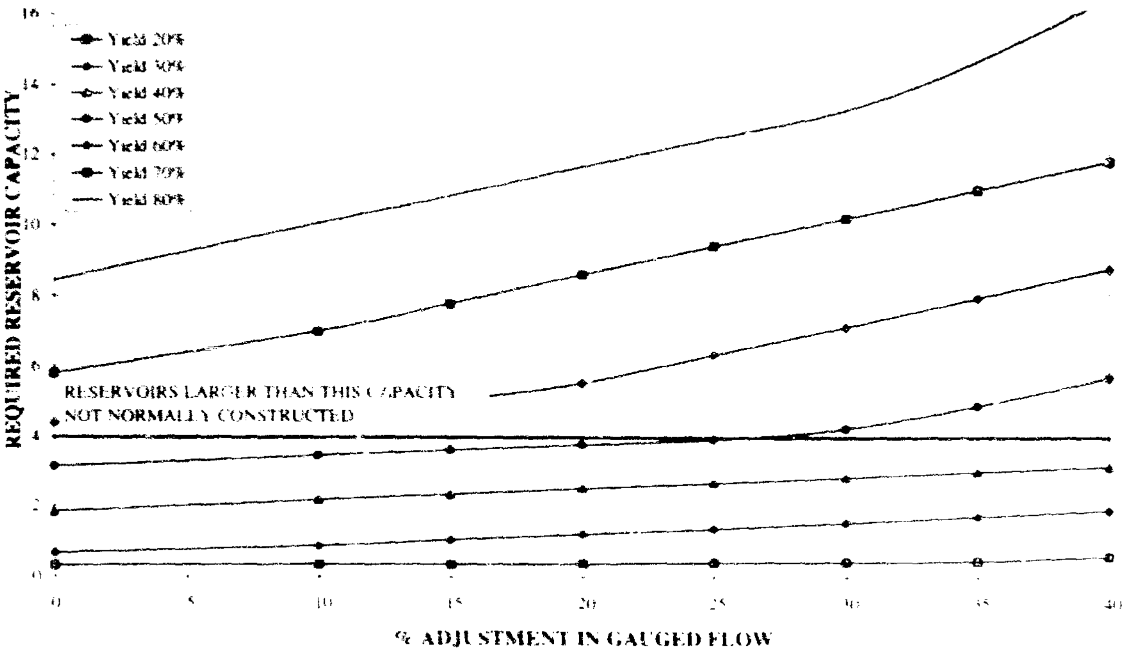


Name of stream	Buffelo River	R2[illegible]
Size of catchment in km^2	1176	
MAR in m^3 * 10^6	17.29	
Coefficient of variation Cv	1.47	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	−10%	−15%	−20%	−25%	−30%	−35%	−40%
20	0.3289	0.3630	0.3775	0.3965	0.4206	0.4425	0.4709	0.6009
30	0.6916	0.9081	1.0649	1.2233	1.3859	1.5507	1.7155	1.8757
40	1.8528	2.1831	2.3398	2.4983	2.6608	2.8256	2.9905	3.1507
50	3.1278	3.4580	3.6148	3.7732	3.9358	[illegible]	[illegible]	[illegible]
60	[illegible]	[illegible]	[illegible]	5.5132	[illegible]	[illegible]	[illegible]	[illegible]
70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
80	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

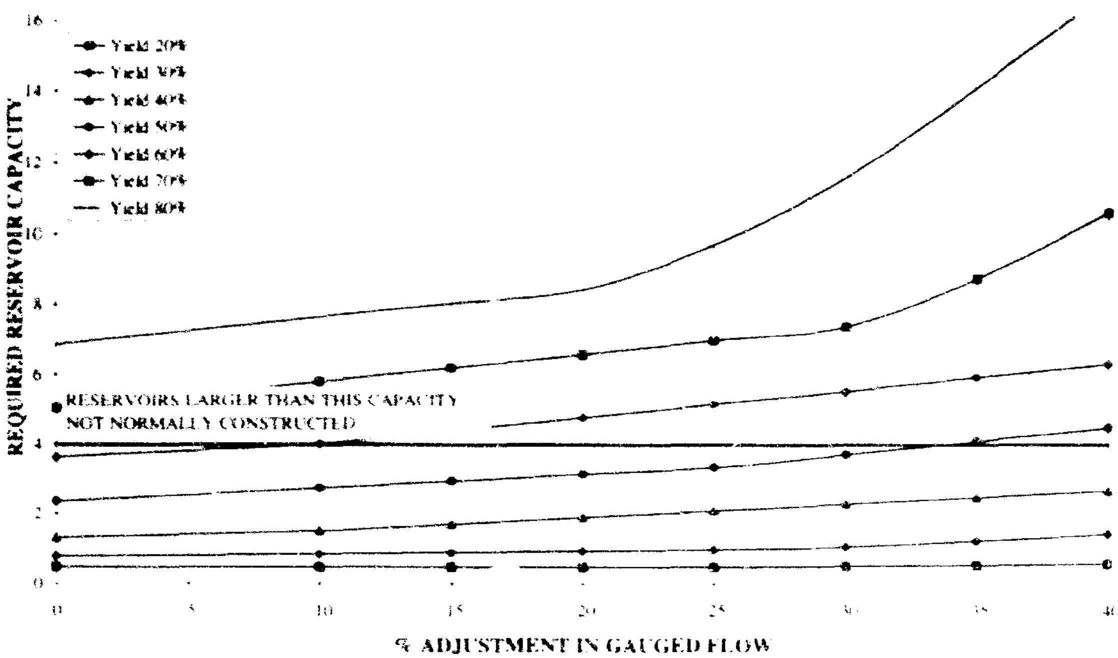


Name of stream	Nahoon River	
Size of catchment in km^2	473	
MAR in m^3 • 10^6	32.33	
Coefficient of variation Cv	1.32	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR. considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.4629	0.4629	0.4629	0.4636	0.4708	0.4958	0.5215	0.5634
30	0.7692	0.8446	0.8860	0.9290	0.9702	1.0417	1.2199	1.4172
40	1.2944	1.5004	1.6925	1.8905	2.0881	2.2876	2.4865	2.6838
50	2.3634	2.7605	2.9591	3.1571	3.3547	3.7041	[illegible]	[illegible]
60	3.6300	[illegible]	[illegible]	4.7333	[illegible]	[illegible]	[illegible]	[illegible]
70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
80	[illegible]	[illegible]	8.0136	8.4037	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

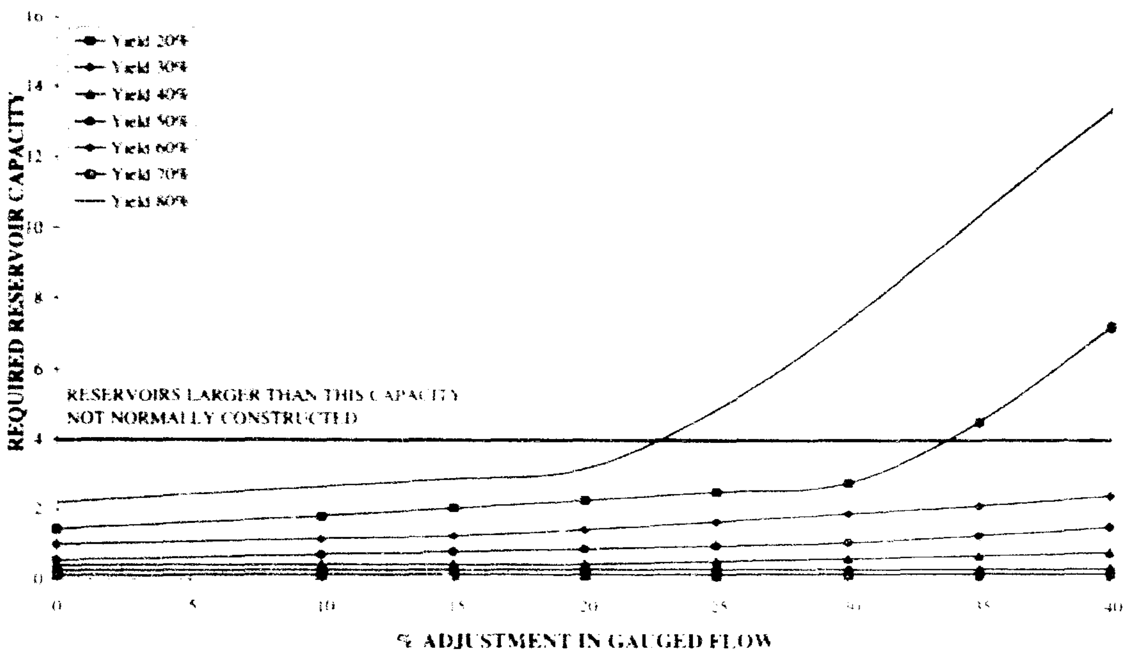


Name of stream	Mgeni River	U2[illegible]
Size of catchment in km^2	928	
MAR in m^3 $\cdot$ 10^6	154.58	
Coefficient of variation Cv	0.60	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1246	0.1373	0.1434	0.1497	0.1569	0.1641	0.1717	0.1803
30	0.2536	0.2706	0.2790	0.2876	0.2963	0.3047	0.3134	0.3244
40	0.3950	0.4122	0.4207	0.4321	0.5155	0.5991	0.6828	0.7660
50	0.5404	0.7071	0.7906	0.8738	0.9572	1.0459	1.2587	1.4921
60	0.9820	1.1487	1.2373	1.4180	1.6508	1.8836	2.1170	2.3831
70	1.4287	1.8094	2.0424	2.2755	2.5091	2.7798	[illegible]	[illegible]
80	2.2009	2.6677	2.9007	3.1774	[illegible]	7.376+	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

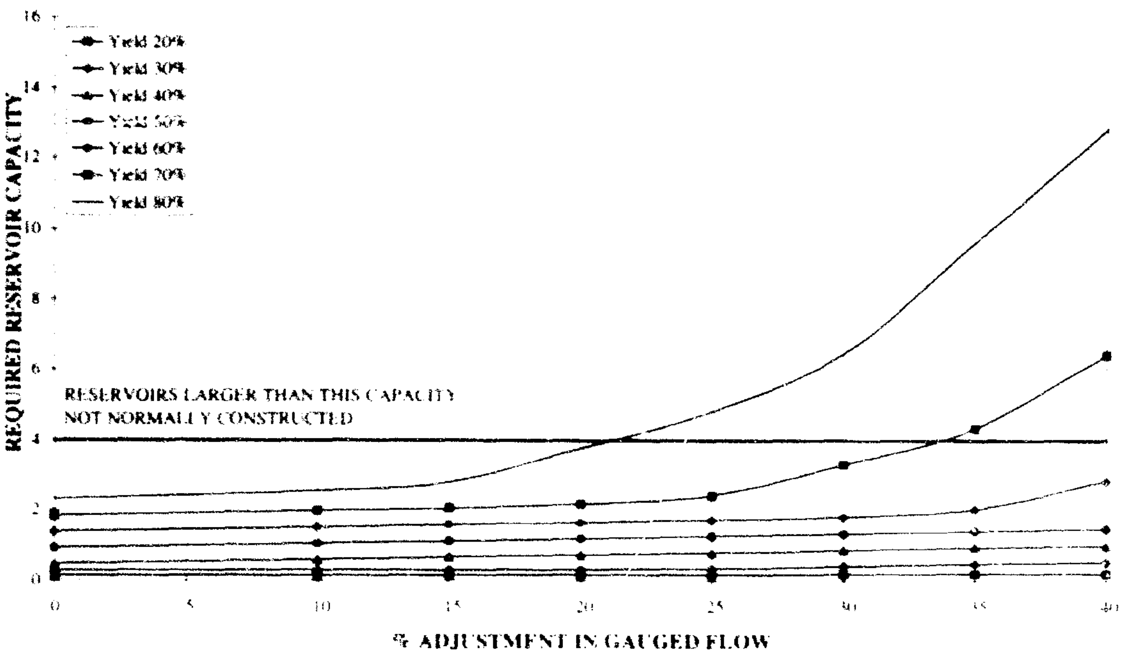


Name of stream	Mgeni River	
Size of catchment in km^2	1644	
MAR in m^3 * 10^6	114.92	
Coefficient of variation	0.68	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1424	0.1579	0.1661	0.1740	0.1817	0.1897	0.1976	0.2054
30	0.2924	0.3079	0.3161	0.3273	0.3579	0.4225	0.4870	0.5534
40	0.4774	0.6058	0.6711	0.7374	0.8044	0.8730	0.9416	1.0105
50	0.9218	1.0565	1.1256	1.1942	1.2627	1.3313	1.4027	1.4746
60	1.3782	1.5149	1.5839	1.6547	1.7261	1.8062	2.0175	2.828+
70	1.8365	1.9776	2.0497	2.1748	2.4074	3.298+	[illegible]	[illegible]
80	2.3016	2.5400	2.797+	3.769+	[illegible]	6.447+	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

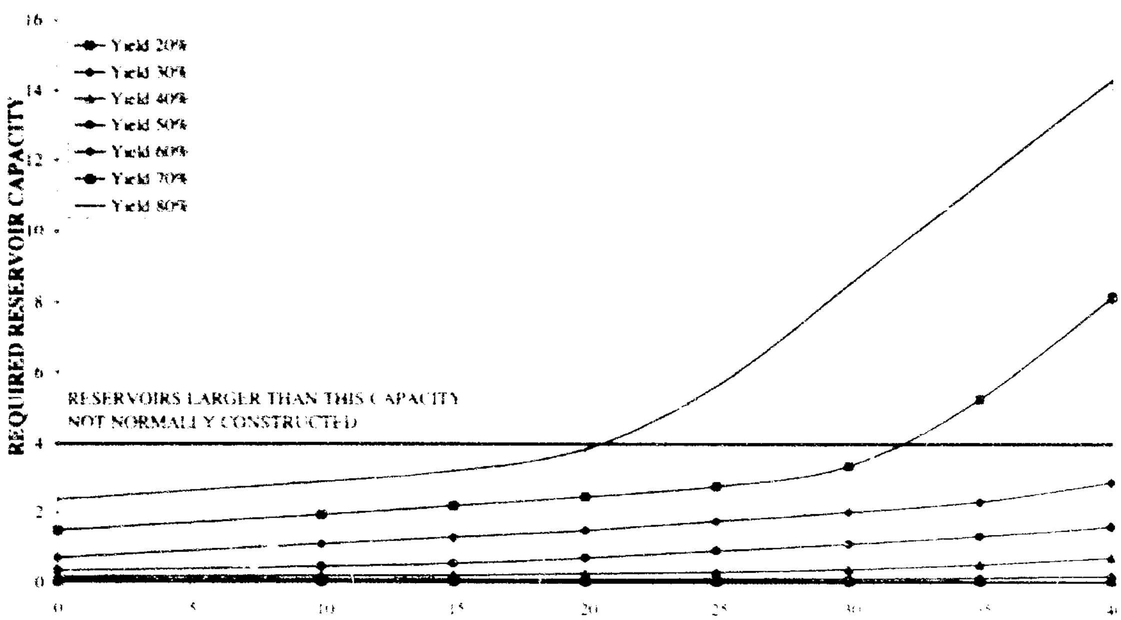
Reservoirs of these capacities are not normally constructed



Name of stream Size of catchment in km² MAR in m³ • 10⁶ Coefficient of variation Cv	Mgeni River 4082 155.47 0.74						U2[illegible]
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0337	0.0403	0.0437	0.0473	0.0514	0.0560	0.0603	0.0646
30	0.0882	0.0968	0.1013	0.1136	0.1299	0.1473	0.1652	0.2089
40	0.1734	0.2084	0.2313	0.2784	0.3299	0.4149	0.5497	0.7448
50	0.3482	0.4727	0.5669	0.7353	0.9307	1.1272	1.3459	1.6080
60	0.7276	1.1172	1.3130	1.5104	1.7720	2.0341	2.3228	2.8785
70	1.4997	1.9365	2.1980	2.4604	2.7620	3.3580	[illegible]	[illegible]
80	2.3630	2.8881	3.2012	3.8372	5.608+	[illegible]	11.39+	14.30+

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

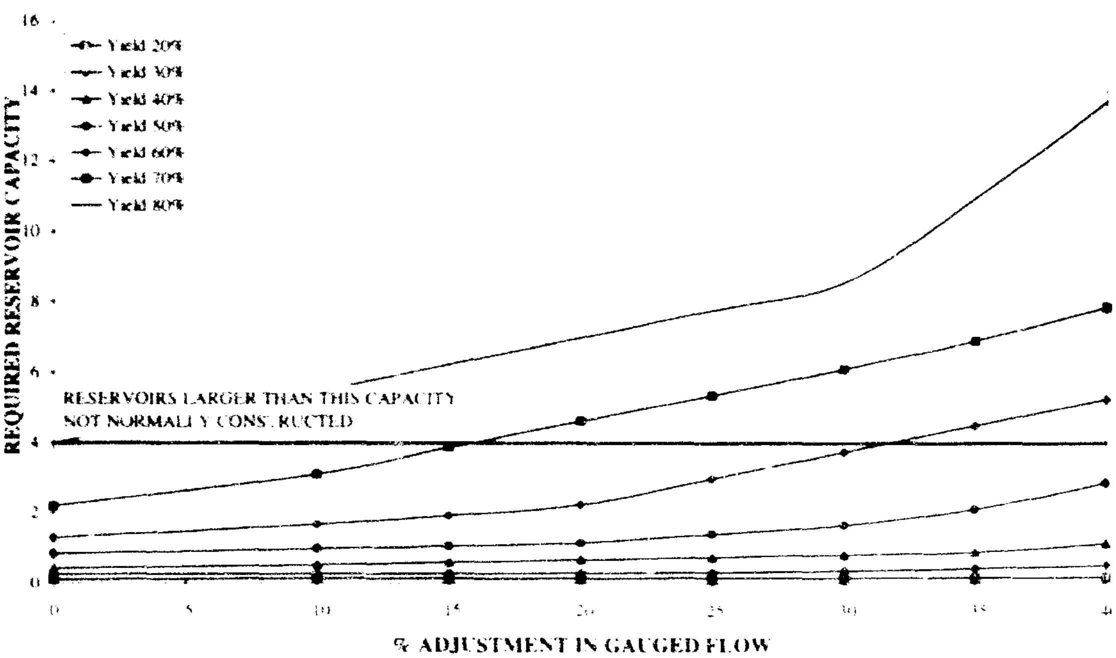


Name of stream	Tongati River	[redacted]
Size of catchment in km²	236	
MAR in m³ • 10⁶	41.30	
Coefficient of variation Cv	0.69	

Gross yield expressed as a percentage of the MAR	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1171	0.1299	0.1374	0.1451	0.1529	0.1604	0.1679	0.1769
30	0.2479	0.2652	0.2802	0.2942	0.3083	0.3543	0.4250	0.4962
40	0.4114	0.5186	0.5898	0.6624	0.7331	0.8080	0.8831	1.1165
50	0.8.71	0.9710	1.0468	1.1480	1.3936	1.6473	2.1190	2.8626
60	1.2873	1.6747	1.9269	2.2471	[redacted]	3.7350	[redacted]	[redacted]
70	2.2050	3.1145	3.8583	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
80	3.9855	5.4752	6.2229	6.9716	[redacted]	[redacted]	[redacted]	[redacted]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

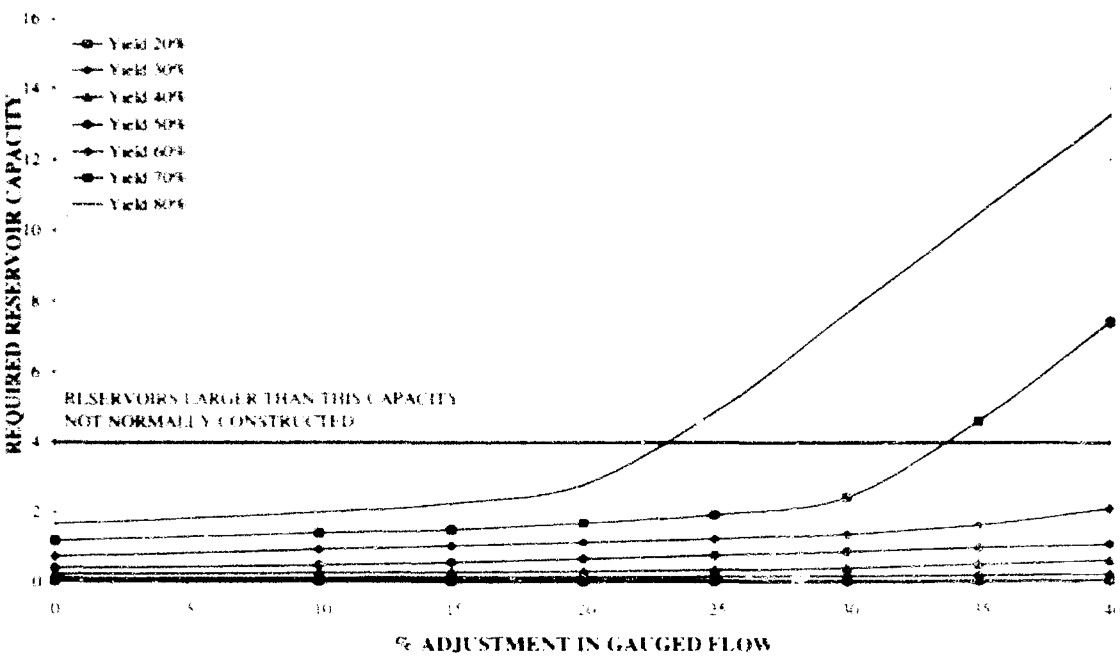


Name of stream	Moloti River
Size of catchment in km^2	377
MAR in $m^3 \cdot 10^6$	66.16
Coefficient of variation Cv	0.57

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	−10%	−15%	−20%	−25%	−30%	−35%	−40%
20	0.0395	0.0468	0.0508	0.0552	0.0608	0.0670	0.0731	0.0841
30	0.1065	0.1256	0.1408	0.1558	0.1732	0.1912	0.2098	0.2392
40	0.2308	0.2671	0.2859	0.3195	0.3659	0.4187	0.5199	0.6216
50 +	0.3995	0.4926	0.5739	0.6746	0.7770	0.8812	0.9851	1.0882
60	0.7289	0.9326	1.0367	1.1401	1.2437	1.3824	1.6434	2.1032
70	1.1920	1.3992	1.5034	1.6984	1.9602	2.4534	[illegible]	[illegible]
80	1.6587	2.0169	2.2787	2.8043	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

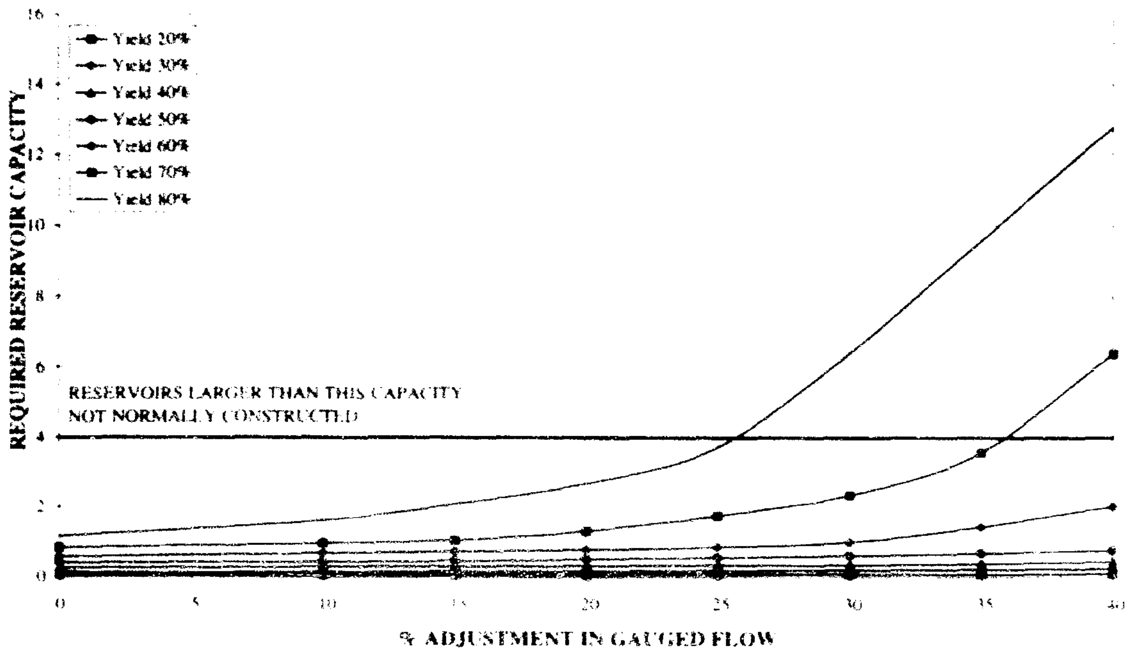
Reservoirs of these capacities are not normally constructed



Name of stream Size of catchment in km^2 MAR in $m^3 \cdot 10^6$ Coefficient of variation Cv	Tugela River 2452 869.98 0.44							
Gross yield expressed as a percentage of the MAR.	**Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.**							
	0%	**-10%**	**-15%**	**-20%**	**-25%**	**-30%**	**-35%**	**-40%**
20	0.0657	0.0708	0.0733	0.0761	0.0797	0.0833	0.0869	0.0925
30	0.1285	0.1388	0.1561	0.1734	0.1907	0.2079	0.2253	0.2425
40	0.2542	0.2888	0.3061	0.3234	0.3406	0.3579	0.3957	0.4473
50	0.4042	[illegible]	0.4561	0.5075	[illegible]	0.6107	0.6733	0.7702
60	0.5677	0.6709	0.7225	0.7742	0.8615	0.9978	1.4340	2.0155
70	0.8344	0.9605	1.0522	1.3070	1.7591	2.3515	3.5753	
80	1.1487	1.6162	2.0843	2.6874	3.7206			

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

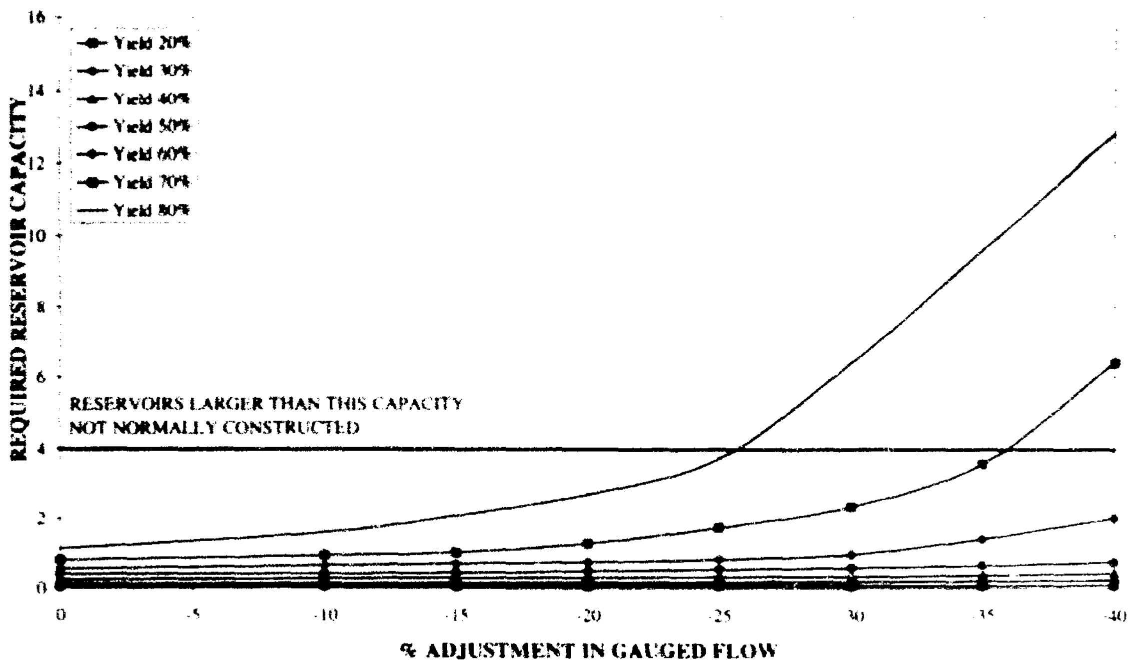


Name of stream	Tugela River						
Size of catchment in km^2	1149						
MAR in m^3 * 10^6	516.99						
Coefficient of variation Cv	0.44						

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0657	0.0708	0.0733	0.0762	0.0797	0.0833	0.0869	0.0925
30	0.1285	0.1388	0.1561	0.1734	0.1907	0.2079	0.2252	0.2425
40	0.2542	0.2888	0.3061	0.3234	0.3407	0.3579	0.3957	0.4473
50	0.4042	0.4388	0.4561	0.5075	0.5591	0.6108	0.6734	0.7703
60	0.5677	0.6709	0.7226	0.7742	0.8615	0.9977	1.4341	2.0156
70	0.8344	0.9605	1.0523	1.3069	1.7589	2.3514	3.5753	
80	1.1487	1.6163	2.0843	2.6873	3.7204			

\+ Critical period starts at the beginning of the record or ends at the end of the record.

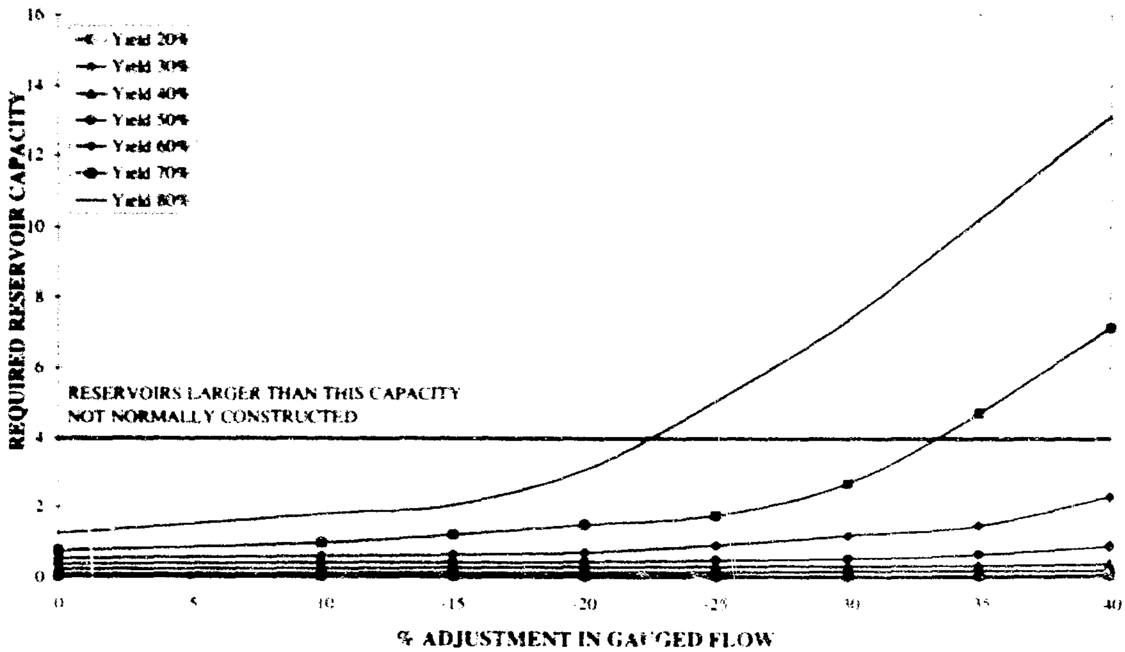
Reservoirs of these capacities are not normally constructed



Name of stream	Mooi River							
Size of catchment in km^2	1546							
MAR in $m^3 \cdot 10^6$	274.97							
Coefficient of variation Cv	0.54							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0331	0.0386	0.0421	0.0454	0.0499	0.0554	0.0649	0.0830
30	0.0887	0.1245	0.1426	0.1606	0.1788	0.1968	0.2149	0.2330
40	0.2383	0.2745	0.2926	0.3106	0.3287	0.3468	0.3649	0.4095
50	0.3883	0.4245	0.4426	0.4606	0.5118	0.5638	0.6755	0.9169
60	0.5383	0.6141	0.6662	0.7287	0.9357	1.2100	1.4844	2.3078
70	0.7685	0.9865	1.2289	1.5032	1.7773	2.6918		
80	1.2477	1.7963	2.0705	3.0768				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

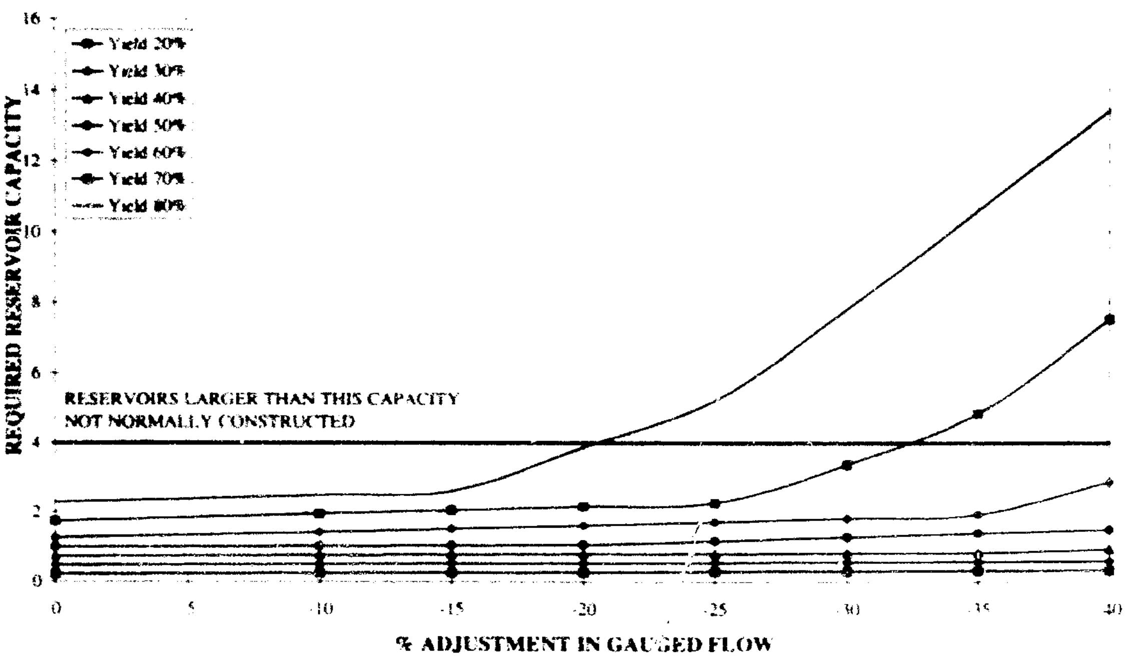


Name of stream	Ngagane River	
Size of catchment in km^2	830	
MAR in $m^3 \cdot 10^6$	110.86	
Coefficient of variation Cv	0.65	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2219	0.2409	0.2563	0.2717	0.2871	0.3024	0.3179	0.3328
30	0.4686	0.4992	0.5146	0.5301	0.5454	0.5607	0.5762	0.5911
40	0.7270	0.7575	0.7730	0.7884	0.8037	0.8191	0.8346	0.9339
50	0.9853	1.0159	1.0313	1.0624	1.1677	1.2730	1.3790	1.4841
60	1.2436	1.4010	1.5069	1.6123	1.7177	1.8245	1.9339	2.8974
70	1.7402	1.9510	2.0569	2.1653	2.2741	3.3803		
80	2.2901	2.5054	2.6268	3.8638				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

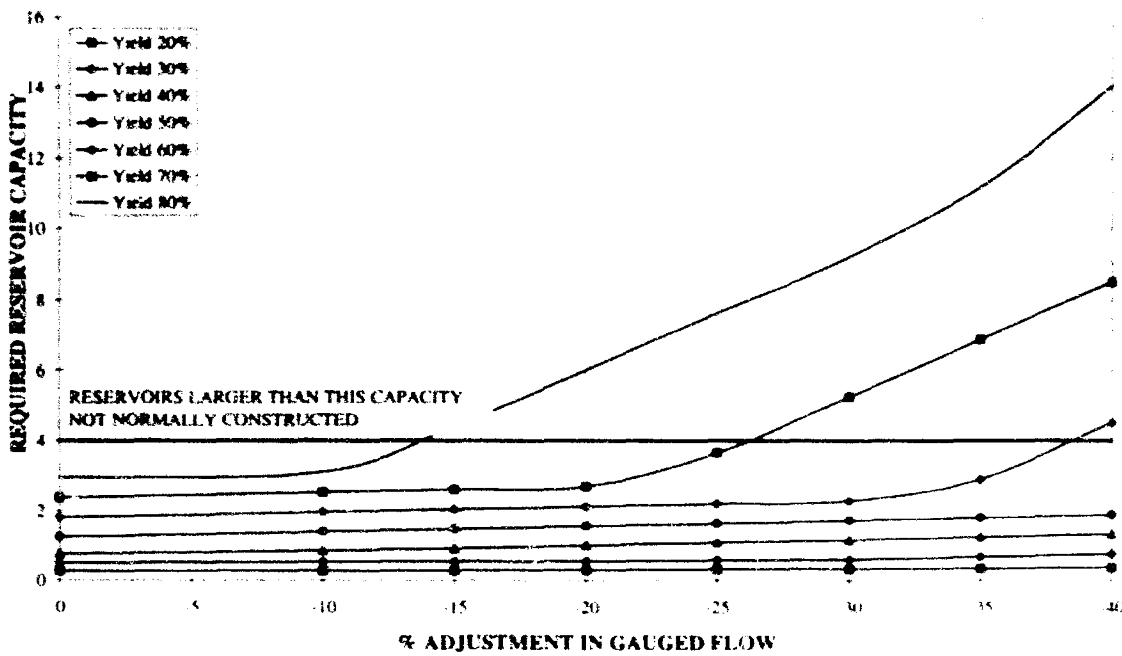
Reservoirs of these capacities are not normally constructed



Name of stream	Slang River							
Size of catchment in km²	604							
MAR in $m^3 \cdot 10^6$	89.73							
Coefficient of variation Cv	0.65							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.2613	0.2701	0.2798	0.2940	0.3077	0.3215	0.3357	0.3495
30	0.4965	0.5241	0.5381	0.5523	0.5660	0.5937	0.6693	0.7474
40	0.7548	0.8419	0.9176	0.9968	1.0760	1.1554	1.2350	1.3141
50	1.2460	1.4046	1.4841	1.5634	1.6426	1.7220	1.8017	1.8807
60	1.8127	1.9712	2.0507	2.1301	2.2093	2.2886	2.8977	
70	2.3793	2.5379	2.6173	2.6967	3.6458			
80	2.9459	3.1045						

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

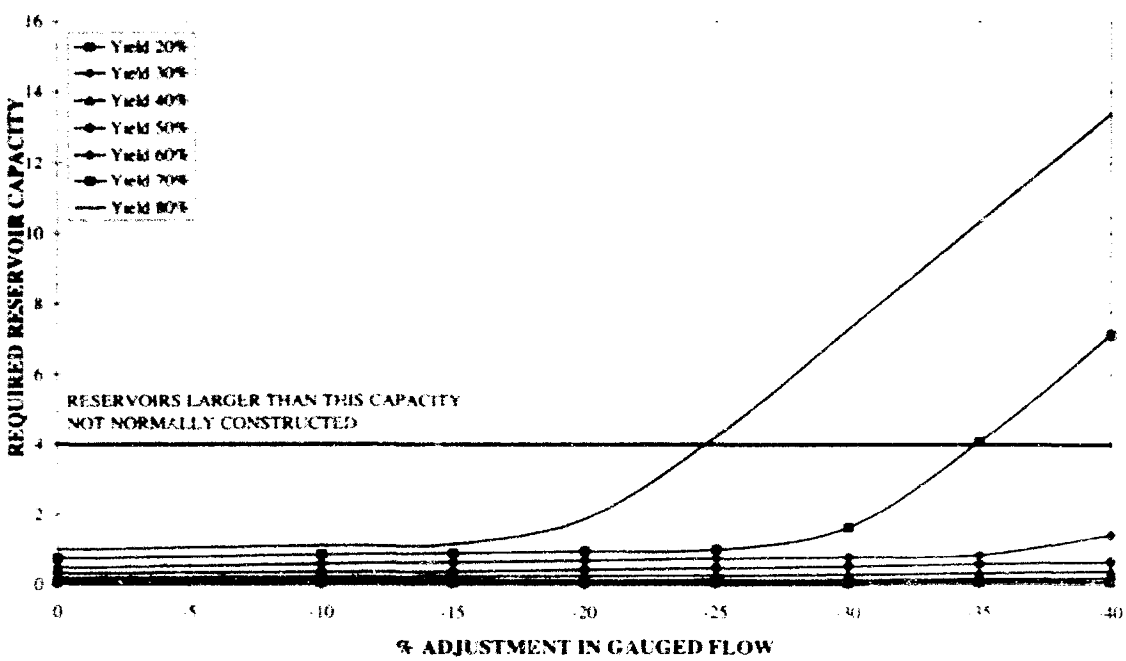


Name of stream	Tugela River
Size of catchment in km^2	28920
MAR in m^3 • 10^6	2848.58
Coefficient of variation Cv	0.32

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0591	0.0649	0.0678	0.0707	0.0735	0.0764	0.0793	0.0822
30	0.1175	0.1232	0.1261	0.1290	0.1319	0.1498	0.1713	0.1927
40	0.1758	0.2141	0.2355	0.2569	0.2784	0.3016	0.3396	0.3930
50	0.3212	0.3651	0.3888	0.4378	0.4912	0.5445	0.5979	0.6513
60	0.4827	0.5894	0.6428	0.6962	0.7495	0.8029	0.8562	1.4148
70	0.7410	0.8477	0.9011	0.9545	1.0078	1.6506		
80	0.9993	1.1061	1.1594	1.8864				

+ Critical period starts at the beginning of the record or ends at the end of the record.

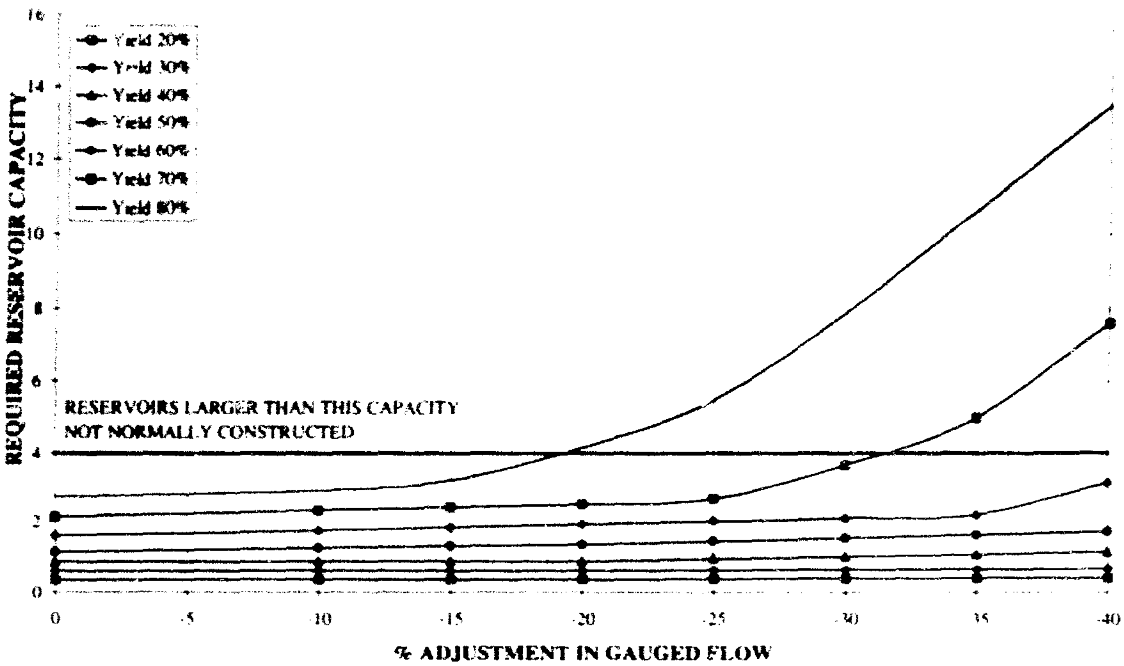
Reservoirs of these capacities are not normally constructed



Name of stream	Sondags River							
Size of catchment in km²	658							
MAR in $m^3 \cdot 10^6$	92.51							
Coefficient of variation Cv	0.67							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.3539	0.3703	0.3779	0.3867	0.3943	0.4028	0.4113	0.4189
30	0.6122	0.6286	0.6362	0.6457	0.6548	0.6648	0.6748	0.6840
40	0.8735	0.8929	0.9020	0.9124	0.9725	1.0350	1.0971	1.1707
50	1.1401	1.2630	1.3240	1.3861	1.4631	1.5550	1.6466	1.7373
60	1.6140	1.7567	1.8473	1.9388	2.0297	2.1216	2.2138	3.1151
70	2.1403	2.3233	2.4139	2.5055	2.6544	3.6337		
80	2.7070	2.8900	3.1748					

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

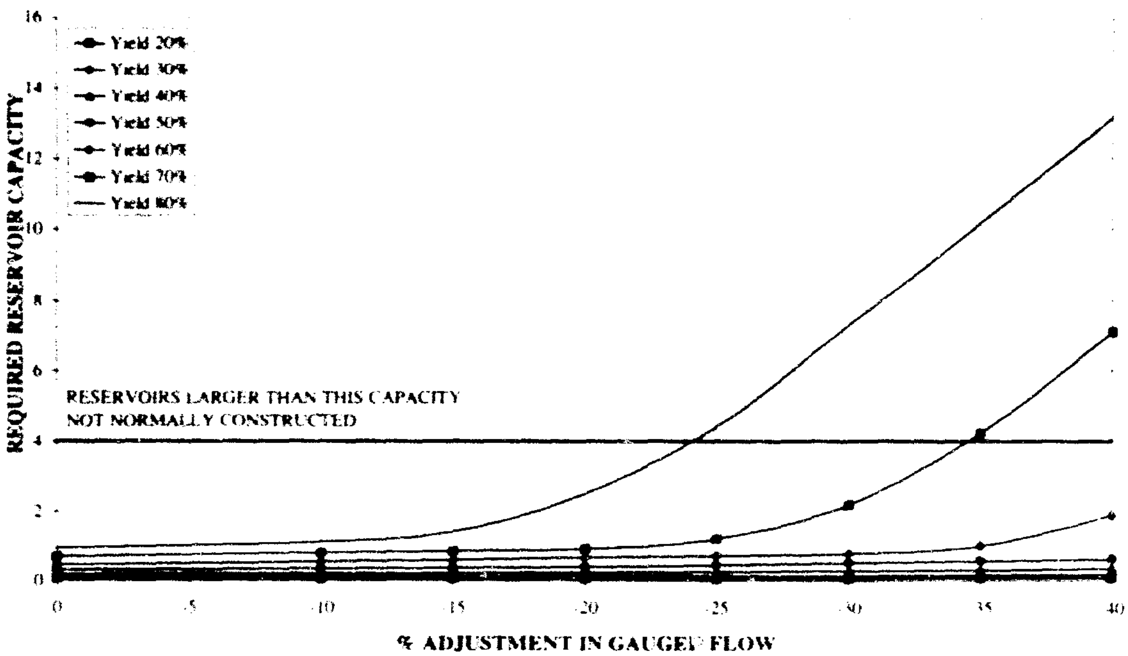


Name of stream	Boesmans River
Size of catchment in km^2	744
MAR in $m^3 \cdot 10^6$	224.50
Coefficient of variation Cv	0.44

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0582	0.0641	0.069	0.0698	0.0728	0.0757	0.0786	0.0816
30	0.1165	0.1224	0.1256	0.1300	0.1344	0.1462	0.1661	0.1860
40	0.1792	0.2082	0.2281	0.2481	0.2686	0.2907	0.3128	0.3677
50	0.3100	0.3523	0.3743	0.4042	0.4597	0.5153	0.5707	0.6260
60	0.4580	0.5517	0.6071	0.6625	0.7180	0.7736	0.9944	1.8821
70	0.6990	0.8100	0.8654	0.9250	1.2122	2.1960		
80	0.9574	1.1298	1.4302	2.5096				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

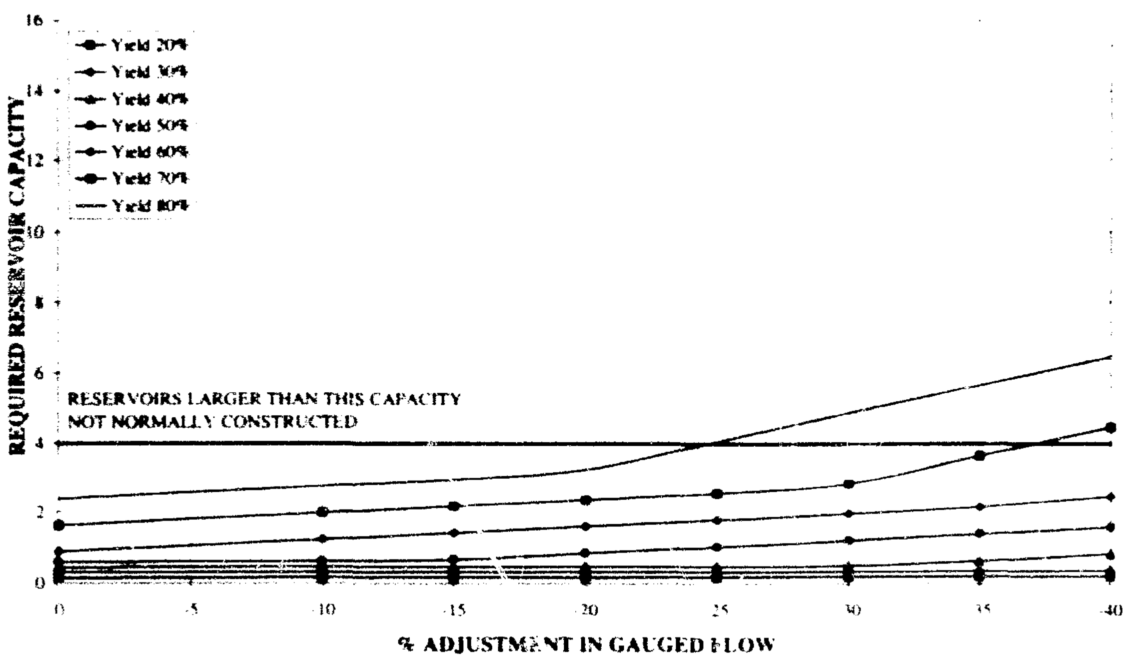
Reservoirs of these capacities are not normally constructed



Name of stream	Mkuze River							
Size of catchment in km²	2571							
MAR in $m^3 \cdot 10^6$	113.51							
Coefficient of variation Cv	0.75							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1494	0.1645	0.1719	0.1796	0.1871	0.1945	0.2121	0.2095
30	0.2994	0.3145	0.3219	0.3296	0.3371	0.3445	0.3521	0.3605
40	0.4494	0.4645	0.4719	0.4809	0.4904	0.5066	0.6448	0.8259
50	0.6010	0.6200	0.6722	0.8509	1.0317	1.2156	1.3997	1.5842
60	0.8783	1.2388	1.4222	1.6063	1.7900	1.9774	2.1720	2.4415
70	1.6288	1.9971	2.1805	2.3722	2.5663	2.8470	3.6444	
80	2.3871	2.7672	2.9610	3.2550				

+ Critical period starts at the beginning of the record or ends at the end of the record.

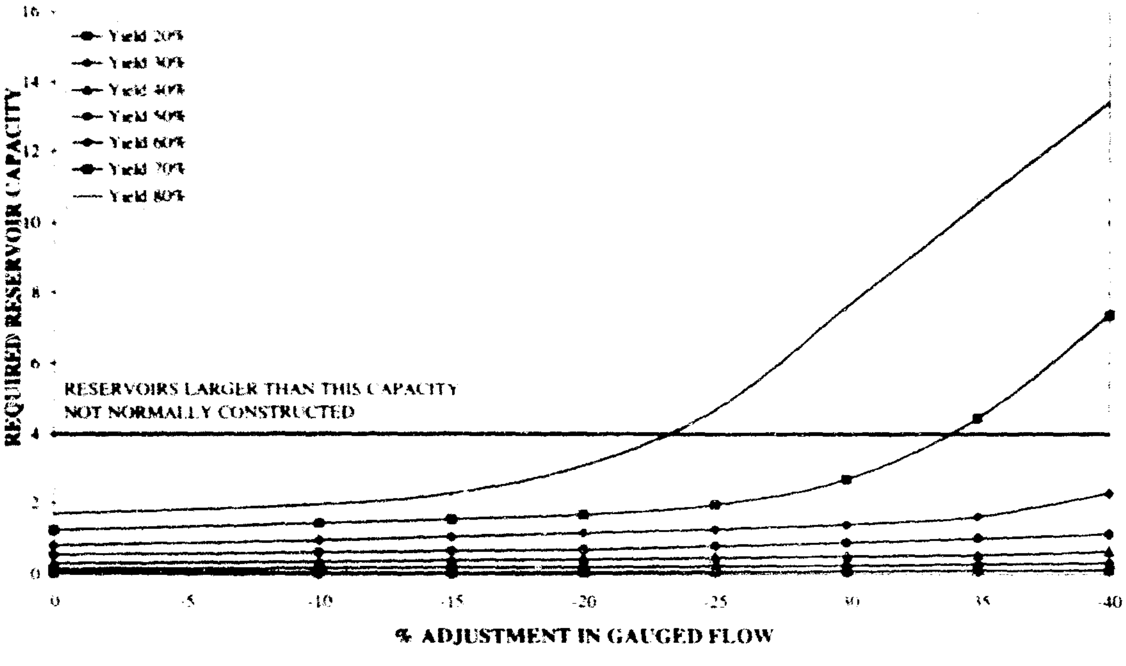
Reservoirs of these capacities are not normally constructed



Name of stream Size of catchment in km^2 MAR in m^3 • 10^6 Coefficient of variation Cv	Phongolo River 7831 1006.99 0.49							
Gross yield expressed as a percentage of the MAR	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.0418	0.0476	0.0531	0.0676	0.0821	0.0966	0.1112	0.1257
30	0.1595	0.1885	0.2031	0.2187	0.2347	0.2559	0.2930	0.3301
40	0.3129	0.3659	0.4030	0.4401	0.4772	0.5142	0.5513	0.6449
50	0.5501	0.6243	0.6614	0.7044	0.8061	0.9081	1.0129	1.1288
60	0.8084	0.9674	1.0692	1.1736	1.2783	1.4095	1.6375	2.3307
70	1.2304	1.4390	1.5532	1.6907	1.9714	2.7191		
80	1.7044	1.9718	2.3054	3.1076				

+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

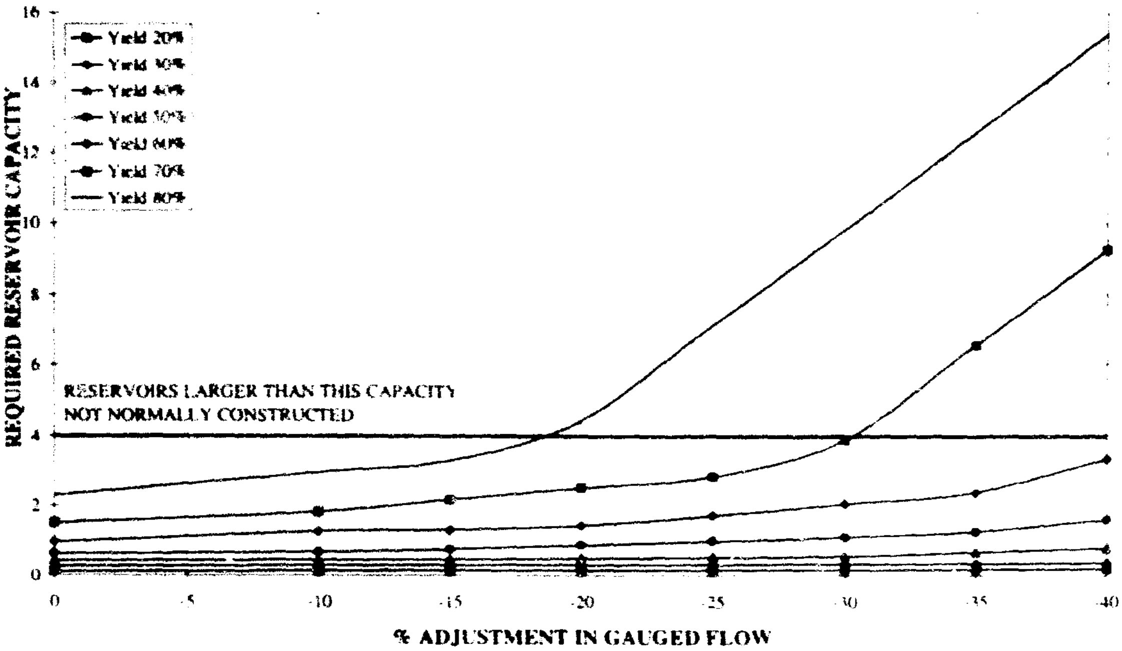


Name of stream	Komati River	
Size of catchment in km^2	5499	
MAR in m^3 • 10^6	543.56	
Coefficient of variation Cv	0.67	

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1141	0.1344	0.1445	0.1546	0.1648	0.1749	0.1850	0.1964
30	0.2725	0.2945	0.3060	0.3174	0.3288	0.3402	0.3516	0.3783
40	0.4384	0.4612	0.4734	0.5044	0.5353	0.5715	0.6878	0.8042
50	0.6305	0.69[illegible]4	0.7725	0.8889	1.0051	1.1233	1.2687	1.5973
60	0.9736	1.2862	1.3240	1.4432	1.7194	2.0482	2.3770	3.328+
70	1.5249	1.8418	2.1704	2.4992	2.8277	3.882+		
80	2.2927	2.9501	3.2787	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed

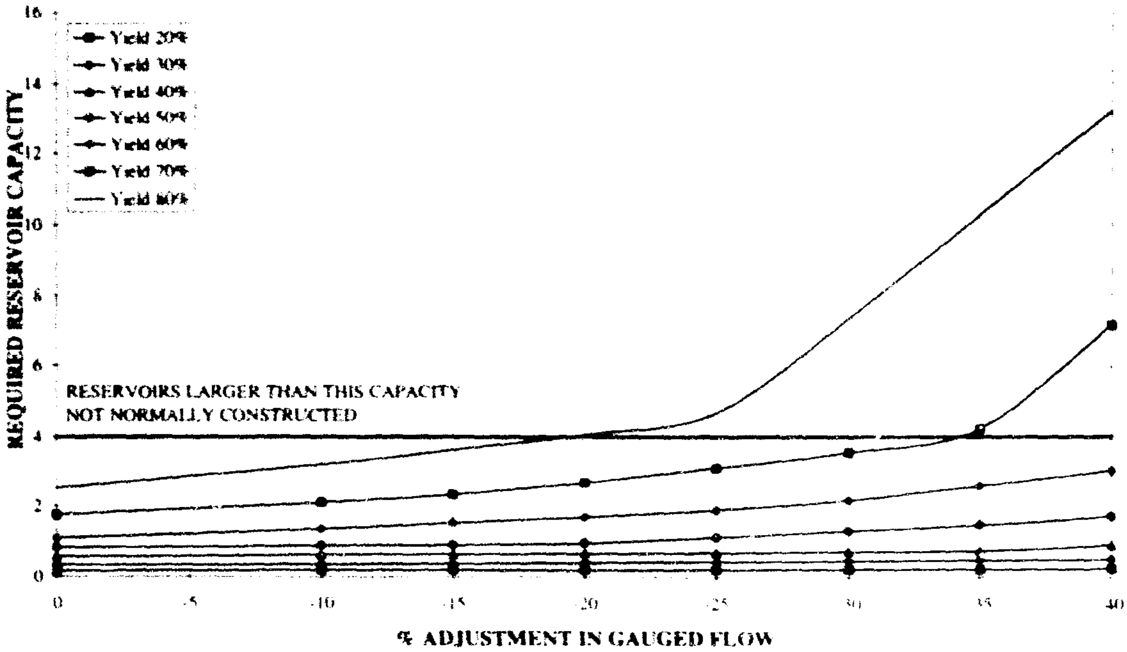


Name of stream	Komati River
Size of catchment in km²	1569
MAR in $m^3 \cdot 10^6$	67.12
Coefficient of variation Cv	0.79

Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1806	0.1939	0.2025	0.2101	0.2174	0.2250	0.2329	0.2422
30	0.3458	0.3630	0.3869	0.4092	0.4319	0.4543	0.4776	0.5005
40	0.5762	0.6213	0.6452	0.6675	0.6902	0.7127	0.7359	0.9004
50	0.8345	0.8797	0.9035	0.9533	1.1252	1.2974	1.4757	1.7143
60	1.0928	1.3504	1.5236	1.6949	1.8864	2.1845	2.6098	3.0397
70	1.7482	2.1050	2.3374	2.6867	3.1157	3.5468	[illegible]	[illegible]
80	2.5168	3.1938	3.6235	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

\+ Critical period starts at the beginning of the record or ends at the end of the record.

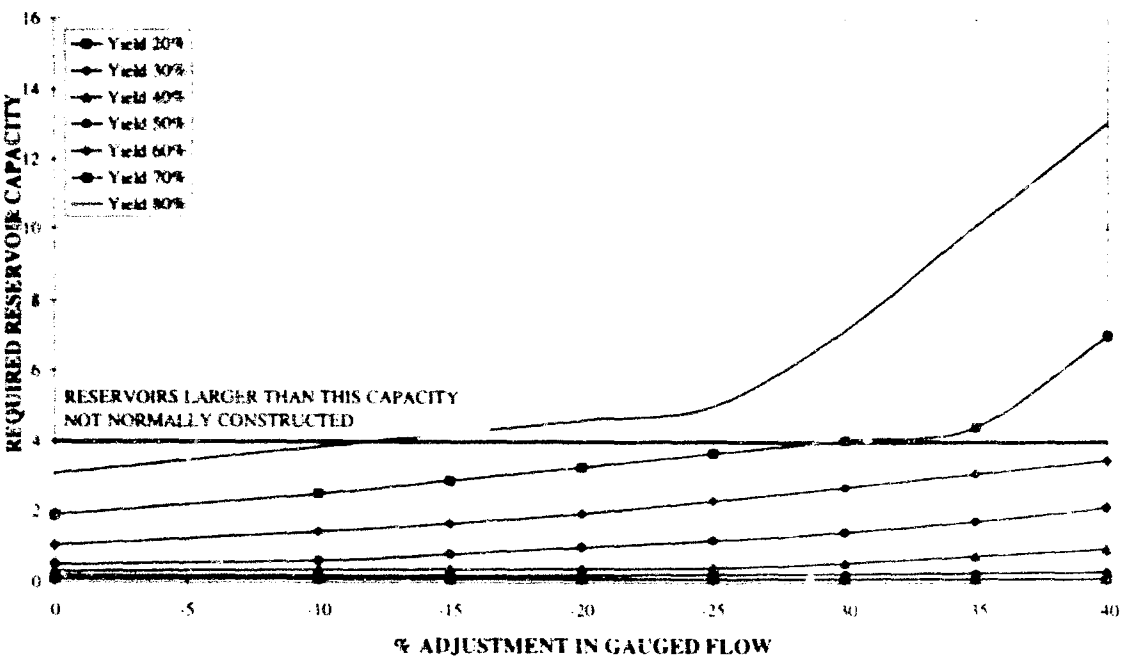
Reservoirs of these capacities are not normally constructed



Name of stream	Komati River							
Size of catchment in km^2	1569							
MAR in $m^3 \cdot 10^6$	246.31							
Coefficient of variation Cv	0.47							
Gross yield expressed as a percentage of the MAR.	Required reservoir capacity as a factor of the MAR, considering the effect of negative adjustments to the existing flow record in the stream. These adjustments are expressed as percentages of the existing flow record.							
	0%	-10%	-15%	-20%	-25%	-30%	-35%	-40%
20	0.1068	0.1111	0.1133	0.1154	0.1176	0.1198	0.1219	0.1241
30	0.1818	0.1861	0.2010	0.2225	0.2444	0.2665	0.2886	0.3106
40	0.3260	0.3701	0.3921	0.4142	0.4361	0.5831	0.7726	0.9629
50	0.5177	0.6352	0.8240	1.0132	1.2032	1.4327	1.7245	2.1111
60	1.0643	1.4443	1.6651	1.9377	2.3008	2.6878	3.0744	3.4611
70	1.8969	2.4916	2.8783	3.2648	3.6507			
80	3.0683	3.8415	[illegible]	[illegible]				

\+ Critical period starts at the beginning of the record or ends at the end of the record.

Reservoirs of these capacities are not normally constructed



APPENDIX: B1

Crump weir with dividing walls
Department of Water Affairs and Forestry Tests.

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)
WMOD1-1s	1.597	2.416	0.269	0.097	0.0345	0.020
WMOD1-1s	1.597	2.416	0.269	0.097	0.0636	0.050
WMOD1-1s	1.597	2.416	0.269	0.097	0.0858	0.080
WMOD1-1s	1.597	2.416	0.269	0.097	0.1070	0.120
WMOD1-1s	1.597	2.416	0.269	0.097	0.1190	0.150
WMOD1-1s	1.597	2.416	0.269	0.097	0.1265	0.177
WMOD1-2s	1.597	2.416	0.176	0.097	0.0352	0.020
WMOD1-2s	1.597	2.416	0.176	0.097	0.0635	0.050
WMOD1-2s	1.597	2.416	0.176	0.097	0.0853	0.080
WMOD1-2s	1.597	2.416	0.176	0.097	0.1076	0.120
WMOD1-2s	1.597	2.416	0.176	0.097	0.1177	0.150
WMOD1-2s	1.597	2.416	0.176	0.097	0.1268	0.177
WMOD1-3s	1.597	2.416	0.085	0.097	0.0360	0.020
WMOD1-3s	1.597	2.416	0.085	0.097	0.0616	0.050
WMOD1-3s	1.597	2.416	0.085	0.097	0.0829	0.080
WMOD1-3s	1.597	2.416	0.085	0.097	0.1014	0.120
WMOD1-3s	1.597	2.416	0.085	0.097	0.1127	0.150
WMOD1-3s	1.597	2.416	0.085	0.097	0.1214	0.177
WMOD2-3s	1.230	2.792	0.089	0.098	0.0433	0.020
WMOD2-3s	1.230	2.792	0.089	0.098	0.0748	0.050
WMOD2-3s	1.230	2.792	0.089	0.098	0.0998	0.080
WMOD2-3s	1.230	2.792	0.089	0.098	0.1172	0.120
WMOD2-3s	1.230	2.792	0.089	0.098	0.1283	0.150
WMOD2-3s	1.230	2.792	0.089	0.098	0.1365	0.177
WMOD2-2s	1.230	2.792	0.173	0.098	0.0433	0.020
WMOD2-2s	1.230	2.792	0.173	0.098	0.0742	0.050
WMOD2-2s	1.230	2.792	0.173	0.098	0.0995	0.080
WMOD2-2s	1.230	2.792	0.173	0.098	0.1172	0.120
WMOD2-2s	1.230	2.792	0.173	0.098	0.1272	0.150
WMOD2-2s	1.230	2.792	0.173	0.098	0.1345	0.177
WMOD2-1s	1.230	2.792	0.268	0.098	0.0423	0.020
WMOD2-1s	1.230	2.792	0.268	0.098	0.0718	0.050
WMOD2-1s	1.230	2.792	0.268	0.098	0.0946	0.080

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)
WMOD2-1s	1.230	2.792	0.268	0.098	0.1100	0.120
WMOD2-1s	1.230	2.792	0.268	0.098	0.1206	0.150
WMOD2-1s	1.230	2.792	0.268	0.098	0.1269	0.177
WMOD3-1s	0.999	3.005	0.268	0.098	0.0473	0.020
WMOD3-1s	0.999	3.005	0.268	0.098	0.0850	0.050
WMOD3-1s	0.999	3.005	0.268	0.098	0.1071	0.080
WMOD3-1s	0.999	3.005	0.268	0.098	0.1227	0.120
WMOD3-1s	0.999	3.005	0.268	0.098	0.1330	0.150
WMOD3-1s	0.999	3.005	0.268	0.098	0.1413	0.177
WMOD3-2s	0.999	3.005	0.185	0.098	0.0486	0.020
WMOD3-2s	0.999	3.005	0.185	0.098	0.0850	0.050
WMOD3-2s	0.999	3.005	0.185	0.098	0.1074	0.080
WMOD3-2s	0.999	3.005	0.185	0.098	0.1229	0.120
WMOD3-2s	0.999	3.005	0.185	0.098	0.1333	0.150
WMOD3-2s	0.999	3.005	0.185	0.098	0.1416	0.177
WMOD3-3s	0.999	3.005	0.103	0.098	0.0454	0.020
WMOD3-3s	0.999	3.005	0.103	0.098	0.0800	0.050
WMOD3-3s	0.999	3.005	0.103	0.098	0.0988	0.080
WMOD3-3s	0.999	3.005	0.103	0.098	0.1136	0.120
WMOD3-3s	0.999	3.005	0.103	0.098	0.1222	0.150
WMOD3-3s	0.999	3.005	0.103	0.098	0.1304	0.177
WMOD4-2s	0.804	3.200	0.183	0.098	0.0228	0.005
WMOD4-2s	0.804	3.200	0.183	0.098	0.0352	0.010
WMOD4-2s	0.804	3.200	0.183	0.098	0.0452	0.015
WMOD4-2s	0.804	3.200	0.183	0.098	0.0542	0.020
WMOD4-2s	0.804	3.200	0.183	0.098	0.0962	0.050
WMOD4-2s	0.804	3.200	0.183	0.098	0.1134	0.080
WMOD4-2s	0.804	3.200	0.183	0.098	0.1284	0.120
WMOD4-2s	0.804	3.200	0.183	0.098	0.1384	0.150
WMOD4-2s	0.804	3.200	0.183	0.098	0.1456	0.177
WMOD4-3s	0.804	3.200	0.103	0.098	0.0338	0.010
WMOD4-3s	0.804	3.200	0.103	0.098	0.0523	0.020
WMOD4-3s	0.804	3.200	0.103	0.098	0.0915	0.050
WMOD4-3s	0.804	3.200	0.103	0.098	0.1058	0.080
WMOD4-3s	0.804	3.200	0.103	0.098	0.1187	0.120
WMOD4-3s	0.804	3.200	0.103	0.098	0.1272	0.150
WMOD4-3s	0.804	3.200	0.103	0.098	0.1332	0.171
WMOD5-2s	0.672	3.332	0.183	0.099	0.0245	0.005
WMOD5-2s	0.672	3.332	0.183	0.099	0.0401	0.010
WMOD5-2s	0.672	3.332	0.183	0.099	0.0520	0.015

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)
WMOD5-2s	0.672	3.332	0.183	0.099	0.0627	0.020
WMOD5-2s	0.672	3.332	0.183	0.099	0.1029	0.050
WMOD5-2s	0.672	3.332	0.183	0.099	0.1183	0.080
WMOD5-2s	0.672	3.332	0.183	0.099	0.1334	0.120
WMOD5-2s	0.672	3.332	0.183	0.099	0.1425	0.150
WMOD5-2s	0.672	3.332	0.183	0.099	0.1504	0.177
WMOD5-3s	0.672	3.332	0.093	0.099	0.0251	0.005
WMOD5-3s	0.672	3.332	0.093	0.099	0.0388	0.010
WMOD5-3s	0.672	3.332	0.093	0.099	0.0496	0.015
WMOD5-3s	0.672	3.332	0.093	0.099	0.0596	0.020
WMOD5-3s	0.672	3.332	0.093	0.099	0.0965	0.050
WMOD5-3s	0.672	3.332	0.093	0.099	0.1097	0.080
WMOD5-3s	0.672	3.332	0.093	0.099	0.1237	0.120
WMOD5-3s	0.672	3.332	0.093	0.099	0.1325	0.150
WMOD5-3s	0.672	3.332	0.093	0.099	0.1385	0.174
WMOD6-3s	0.670	3.332	0.121	0.071	0.0418	0.011
WMOD6-3s	0.670	3.332	0.121	0.071	0.0616	0.020
WMOD6-3s	0.670	3.332	0.121	0.071	0.0868	0.050
WMOD6-3s	0.670	3.332	0.121	0.071	0.0999	0.080
WMOD6-3s	0.670	3.332	0.121	0.071	0.1144	0.120
WMOD6-3s	0.670	3.332	0.121	0.071	0.1240	0.150
WMOD6-3s	0.670	3.332	0.121	0.071	0.1309	0.175
WMOD6-2s	0.670	3.332	0.211	0.071	0.0379	0.010
WMOD6-2s	0.670	3.332	0.211	0.071	0.0594	0.020
WMOD6-2s	0.670	3.332	0.211	0.071	0.0835	0.050
WMOD6-2s	0.670	3.332	0.211	0.071	0.0965	0.080
WMOD6-2s	0.670	3.332	0.211	0.071	0.1100	0.120
WMOD6-2s	0.670	3.332	0.211	0.071	0.1191	0.150
WMOD6-2s	0.670	3.332	0.211	0.071	0.1253	0.175

APPENDIX: B2

Crump weir without dividing walls
Department of Water Affairs and Foresty Tests

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)
WMOD1-1s	1.597	2.416	0.269	0.097	0.0359	0.020
WMOD1-1s	1.597	2.416	0.269	0.097	0.0644	0.050
WMOD1-1s	1.597	2.416	0.269	0.097	0.0877	0.080
WMOD1-1s	1.597	2.416	0.269	0.097	0.1111	0.120
WMOD1-1s	1.597	2.416	0.269	0.097	0.1222	0.150
WMOD1-1s	1.597	2.416	0.269	0.097	0.1309	0.177
WMOD1-2s	1.597	2.416	0.176	0.097	0.0356	0.020
WMOD1-2s	1.597	2.416	0.176	0.097	0.0643	0.050
WMOD1-2s	1.597	2.416	0.176	0.097	0.0877	0.080
WMOD1-2s	1.597	2.416	0.176	0.097	0.1110	0.120
WMOD1-2s	1.597	2.416	0.176	0.097	0.1225	0.150
WMOD1-2s	1.597	2.416	0.176	0.097	0.1311	0.177
WMOD1-3s	1.597	2.416	0.085	0.097	0.0348	0.020
WMOD1-3s	1.597	2.416	0.085	0.097	0.0642	0.050
WMOD1-3s	1.597	2.416	0.085	0.097	0.0873	0.080
WMOD1-3s	1.597	2.416	0.085	0.097	0.1091	0.120
WMOD1-3s	1.597	2.416	0.085	0.097	0.1207	0.150
WMOD1-3s	1.597	2.416	0.085	0.097	0.1290	0.177
WMOD2-3s	1.230	2.792	0.089	0.098	0.0435	0.020
WMOD2-3s	1.230	2.792	0.089	0.098	0.0761	0.050
WMOD2-3s	1.230	2.792	0.089	0.098	0.1032	0.080
WMOD2-3s	1.230	2.792	0.089	0.098	0.1216	0.120
WMOD2-3s	1.230	2.792	0.089	0.098	0.1314	0.150
WMOD2-3s	1.230	2.792	0.089	0.098	0.1388	0.177
WMOD2-2s	1.230	2.792	0.173	0.098	0.0438	0.020
WMOD2-2s	1.230	2.792	0.173	0.098	0.0767	0.050
WMOD2-2s	1.230	2.792	0.173	0.098	0.1044	0.080
WMOD2-2s	1.230	2.792	0.173	0.098	0.1232	0.120
WMOD2-2s	1.230	2.792	0.173	0.098	0.1330	0.150
WMOD2-2s	1.230	2.792	0.173	0.098	0.1409	0.177
WMOD2-1s	1.230	2.792	0.268	0.098	0.0433	0.020
WMOD2-1s	1.230	2.792	0.268	0.098	0.0764	0.050
WMOD2-1s	1.230	2.792	0.268	0.098	0.1037	0.080

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)
WMOD2-1s	1.230	2.792	0.268	0.098	0.1222	0.120
WMOD2-1s	1.230	2.792	0.268	0.098	0.1337	0.150
WMOD2-1s	1.230	2.792	0.268	0.098	0.1405	0.177
WMOD3-1s	0.999	3.005	0.268	0.098	0.0471	0.020
WMOD3-1s	0.999	3.005	0.268	0.098	0.0886	0.050
WMOD3-1s	0.999	3.005	0.268	0.098	0.1132	0.080
WMOD3-1s	0.999	3.005	0.268	0.098	0.1297	0.120
WMOD3-1s	0.999	3.005	0.268	0.098	0.1400	0.150
WMOD3-1s	0.999	3.005	0.268	0.098	0.1490	0.177
WMOD3-2s	0.999	3.005	0.185	0.098	0.0478	0.020
WMOD3-2s	0.999	3.005	0.185	0.098	0.0882	0.050
WMOD3-2s	0.999	3.005	0.185	0.098	0.1131	0.080
WMOD3-2s	0.999	3.005	0.185	0.098	0.1295	0.120
WMOD3-2s	0.999	3.005	0.18[illegible]	0.098	0.1400	0.150
WMOD3-2s	0.999	3.005	0.18[illegible]	0.098	0.1486	0.177
WMOD3-3s	0.999	3.005	0.10[illegible]	0.098	0.0470	0.020
WMOD3-3s	0.999	3.005	0.103	0.098	0.0881	0.050
WMOD3-3s	0.999	3.005	0.103	0.098	0.1124	0.080
WMOD3-3s	0.999	3.005	0.103	0.098	0.1286	0.120
WMOD3-3s	0.999	3.005	0.103	0.098	0.1386	0.150
WMOD3-3s	0.999	3.005	0.103	0.098	0.1475	0.177
WMOD4-2s	0.804	3.200	0.183	0.098	0.0219	0.005
WMOD4-2s	0.804	3.200	0.183	0.098	0.0354	0.010
WMOD4-2s	0.804	3.200	0.183	0.098	0.0452	0.015
WMOD4-2s	0.804	3.200	0.183	0.098	0.0554	0.020
WMOD4-2s	0.804	3.200	0.183	0.098	0.1018	0.050
WMOD4-2s	0.804	3.200	0.183	0.098	0.1196	0.080
WMOD4-2s	0.804	3.200	0.183	0.098	0.1356	0.120
WMOD4-2s	0.804	3.200	0.183	0.098	0.1454	0.150
WMOD4-2s	0.804	3.200	0.183	0.098	0.1530	0.177
WMOD4-3s	0.804	3.200	0.103	0.098	0.0350	0.010
WMOD4-3s	0.804	3.200	0.103	0.098	0.0551	0.020
WMOD4-3s	0.804	3.200	0.103	0.098	0.1023	0.050
WMOD4-3s	0.804	3.200	0.103	0.098	0.1205	0.080
WMOD4-3s	0.804	3.200	0.103	0.098	0.1354	0.120
WMOD4-3s	0.804	3.200	0.103	0.098	0.1454	0.150
WMOD4-3s	0.804	3.200	0.103	0.098	0.1506	0.172
WMOD5-2s	0.672	3.332	0.183	0.099	0.0247	0.005
WMOD5-2s	0.672	3.332	0.183	0.099	0.0409	0.010
WMOD5-2s	0.672	3.332	0.183	0.099	0.0520	0.015

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)
WMOD5-2s	0.672	3.332	0.183	0.099	0.0633	0.020
WMOD5-2s	0.672	3.332	0.183	0.099	0.1086	0.050
WMOD5-2s	0.672	3.332	0.183	0.099	0.1246	0.080
WMOD5-2s	0.672	3.332	0.183	0.099	0.1397	0.120
WMOD5-2s	0.672	3.332	0.183	0.099	0.1503	0.150
WMOD5-2s	0.672	3.332	0.183	0.099	0.1567	0.177
WMOD5-3s	0.672	3.332	0.093	0.099	0.0249	0.005
WMOD5-3s	0.672	3.332	0.093	0.099	0.0396	0.010
WMOD5-3s	0.672	3.332	0.093	0.099	0.0519	0.015
WMOD5-3s	0.672	3.332	0.093	0.099	0.0628	0.020
WMOD5-3s	0.672	3.332	0.093	0.099	0.1084	0.050
WMOD5-3s	0.672	3.332	0.093	0.099	0.1241	0.080
WMOD5-3s	0.672	3.332	0.093	0.099	0.1396	0.120
WMOD5-3s	0.672	3.332	0.093	0.099	0.1497	0.150
WMOD5-3s	0.672	3.332	0.093	0.099	0.1559	0.174
WMOD6-3s	0.670	3.332	0.121	0.071	0.0388	0.010
WMOD6-3s	0.670	3.332	0.121	0.071	0.0622	0.020
WMOD6-3s	0.670	3.332	0.121	0.071	0.0898	0.050
WMOD6-3s	0.670	3.332	0.121	0.071	0.1037	0.080
WMOD6-3s	0.670	3.332	0.121	0.071	0.1180	0.120
WMOD6-3s	0.670	3.332	0.121	0.071	0.1279	0.150
WMOD6-3s	0.670	3.332	0.121	0.071	0.1340	0.177
WMOD6-2s	0.670	3.332	0.211	0.071	0.0397	0.010
WMOD6-2s	0.670	3.332	0.211	0.071	0.0615	0.020
WMOD6-2s	0.670	3.332	0.211	0.071	0.0896	0.050
WMOD6-2s	0.670	3.332	0.211	0.071	0.1036	0.080
WMOD6-2s	0.670	3.332	0.211	0.071	0.1184	0.120
WMOD6-2s	0.670	3.332	0.211	0.071	0.1285	0.150
WMOD6-2s	0.670	3.332	0.211	0.071	0.1350	0.175

APPENDIX: B3

Crump weir with dividing walls
University of Stellenbosch Tests

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_{meas} (m^3/s)	Q_{weir} (m^3/s)	Q_m (m^3/s)
C1	1.197	1.780	0.171	0.107	0.0755	0.0490	0.0497	0.0494
C2	1.197	1.780	0.171	0.107	0.0959	0.0719	0.0728	0.0724
C3	1.197	1.780	0.171	0.107	0.1232	0.1200	0.1220	0.1210
C4	1.197	1.780	0.171	0.107	0.1353	0.1510	0.1520	0.1515
C5	1.197	1.780	0.171	0.107	0.1536	0.2000	0.2040	0.2020
C6	1.197	1.780	0.171	0.107	0.1834	0.3000	0.3010	0.3005
C7	1.197	1.780	0.171	0.107	0.2080	0.3990	0.3950	0.3970
C8	0.735	2.242	0.171	0.106	0.1523	0.1500	0.1510	0.1505
C9	0.735	2.242	0.171	0.106	0.1708	0.2000	0.2020	0.2010
C10	0.735	2.242	0.171	0.106	0.2001	0.3000	0.3010	0.3005
C11	0.735	2.242	0.171	0.106	0.2266	0.4000	0.3930	0.3965
C12	0.479	2.498	0.171	0.107	0.1770	0.1990	0.2020	0.2005
C13	0.479	2.498	0.171	0.107	0.2049	0.3010	0.2980	0.2995
C14	0.479	2.498	0.171	0.107	0.2305	0.4000	0.3960	0.3980
C15	0.479	2.498	0.089	0.107	0.1206	0.0702	0.0713	0.0708
C16	0.479	2.498	0.089	0.107	0.1339	0.1010	0.1030	0.1020
C17	0.479	2.498	0.089	0.107	0.1685	0.2000	0.2030	0.2015
C18	0.479	2.498	0.089	0.107	0.1949	0.3000	0.2980	0.2990
C19	0.479	2.498	0.089	0.107	0.2212	0.4000	0.3980	0.3990
C20	0.735	2.242	0.089	0.107	0.1145	0.0802	0.0811	0.0807
C21	0.735	2.242	0.089	0.107	0.1313	0.1200	0.1220	0.1210
C22	0.735	2.242	0.089	0.107	0.1575	0.2000	0.2020	0.2010
C23	0.735	2.242	0.089	0.107	0.1836	0.3000	0.2980	0.2990
C24	0.735	2.242	0.089	0.107	0.2073	0.4010	0.3970	0.3990
C25	1.197	1.780	0.089	0.107	0.1258	0.1500	0.1520	0.1510
C26	1.197	1.780	0.089	0.107	0.1449	0.2000	0.2010	0.2005
C27	1.197	1.780	0.089	0.107	0.1748	0.3000	0.3000	0.3000
C28	1.197	1.780	0.089	0.107	0.1989	0.4010	0.3970	0.3990

APPENDIX: B4

Crump weir without dividing walls
University of Stellenbosch Tests

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_{meas} (m^3/s)	Q_{weir} (m^3/s)	Q_m (m^3/s)
C1	1.197	1.780	0.171	0.107	0.0782	0.0490	0.0501	0.0495
C2	1.197	1.780	0.171	0.107	0.0985	0.0719	0.0717	0.0718
C3	1.197	1.780	0.171	0.107	0.1305	0.1210	0.1214	0.1212
C4	1.197	1.780	0.171	0.107	0.1431	0.1500	0.1501	0.1501
C5	1.197	1.780	0.171	0.107	0.1629	0.2000	0.2029	0.2015
C6	1.197	1.780	0.171	0.107	0.1944	0.3000	0.2971	0.2986
C7	1.197	1.780	0.171	0.107	0.2208	0.3990	0.3916	0.3953
C8	0.735	2.242	0.171	0.106	0.1618	0.1500	0.1507	0.1504
C9	0.735	2.242	0.171	0.106	0.1810	0.2010	0.2016	0.2013
C10	0.735	2.242	0.171	0.106	0.2127	0.3010	0.2985	0.2998
C11	0.735	2.242	0.171	0.106	0.2394	0.3990	0.3974	0.3982
C12	0.479	2.498	0.171	0.107	0.1918	0.2000	0.2024	0.2012
C13	0.479	2.498	0.171	0.107	0.2210	0.2990	0.2981	0.2986
C14	0.479	2.498	0.171	0.107	0.2496	0.3970	0.3956	0.3963
C15	0.479	2.498	0.089	0.107	0.1362	0.0698	0.0712	0.0705
C16	0.479	2.498	0.089	0.107	0.1514	0.1010	0.1028	0.1019
C17	0.479	2.498	0.089	0.107	0.1894	0.2000	0.2035	0.2018
C18	0.479	2.498	0.089	0.107	0.2192	0.3000	0.2972	0.2986
C19	0.479	2.498	0.089	0.107	0.2451	0.3980	0.3970	0.3975
C20	0.735	2.242	0.089	0.107	0.1304	0.0807	0.0818	0.0813
C21	0.735	2.242	0.089	0.107	0.1488	0.1200	0.1214	0.1207
C22	0.735	2.242	0.089	0.107	0.1783	0.2000	0.2027	0.2014
C23	0.735	2.242	0.089	0.107	0.2089	0.3000	0.2975	0.2988
C24	0.735	2.242	0.089	0.107	0.2350	0.3990	0.3979	0.3985
C25	1.197	1.780	0.089	0.107	0.1420	0.1500	0.1522	0.1511
C26	1.197	1.780	0.089	0.107	0.1594	0.2000	0.2016	0.2008
C27	1.197	1.780	0.089	0.107	0.1897	0.3000	0.2975	0.2988
C28	1.197	1.780	0.089	0.107	0.2165	0.3990	0.3974	0.3982

APPENDIX: B5

Thin-plate weir with dividing walls
University of Stellenbosch Tests

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_{meas} (m^3/s)	Q_{weir} (m^3/s)	Q_m (m^3/s)
S01	1.177	1.759	0.040	0.050	0.0600	0.050	0.051	0.0505
S02	1.177	1.759	0.040	0.050	0.1110	0.200	0.202	0.2010
S03	1.177	1.759	0.040	0.050	0.1350	0.303	0.304	0.3035
S04	1.177	1.759	0.091	0.050	0.0700	0.050	0.058	0.0540
S05	1.177	1.759	0.091	0.050	0.1260	0.200	0.200	0.2000
S06	1.177	1.759	0.091	0.050	0.1740	0.400	0.392	0.3960
S10	1.177	1.759	0.193	0.050	0.1330	0.201	0.206	0.2035
S11	1.177	1.759	0.193	0.050	0.1650	0.300	0.297	0.2985
S12	1.177	1.759	0.193	0.050	0.1930	0.401	0.393	0.3970
S13	1.174	1.761	0.193	0.100	0.1180	0.102	0.104	0.1030
S14	1.174	1.761	0.193	0.100	0.1600	0.202	0.207	0.2045
S15	1.174	1.761	0.193	0.100	0.2190	0.399	0.395	0.3970
S16	1.174	1.761	0.290	0.103	0.1610	0.196	0.199	0.1975
S17	1.174	1.761	0.290	0.103	0.1960	0.301	0.301	0.3010
S18	1.174	1.761	0.290	0.103	0.2220	0.400	0.397	0.3985
S19	0.735	2.196	0.050	0.050	0.0690	0.051	0.052	0.0515
S20	0.735	2.196	0.050	0.050	0.1210	0.201	0.203	0.2020
S21	0.735	2.196	0.050	0.050	0.1420	0.300	0.299	0.2995
S22H	0.739	2.196	0.100	0.050	0.0730	0.049	0.050	0.0495
S23H	0.739	2.196	0.100	0.050	0.1320	0.201	0.201	0.2010
S24H	0.739	2.196	0.100	0.050	0.1820	0.400	0.394	0.3970
S25	0.738	2.198	0.100	0.100	0.1240	0.100	0.100	0.1000
S26	0.738	2.198	0.100	0.100	0.1620	0.200	0.202	0.2010
S27	0.738	2.198	0.100	0.100	0.2090	0.399	0.402	0.4005
S28	0.735	2.203	0.100	0.199	0.1960	0.200	0.201	0.2005
S29	0.735	2.203	0.100	0.199	0.2250	0.301	0.301	0.3010
S30	0.735	2.203	0.100	0.199	0.2500	0.399	0.397	0.3980
S31	0.736	2.202	0.205	0.051	0.1030	0.099	0.102	0.1005
S32	0.736	2.202	0.205	0.051	0.1430	0.200	0.204	0.2020
S33	0.736	2.202	0.205	0.051	0.2010	0.399	0.397	0.3980
S34	0.740	2.196	0.205	0.100	0.1310	0.099	0.099	0.0990
S35	0.740	2.196	0.205	0.100	0.1730	0.199	0.200	0.1995
S36	0.740	2.196	0.205	0.100	0.2240	0.398	0.393	0.3955
S37	0.740	2.196	0.206	0.201	0.2210	0.197	0.199	0.1980

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_{man} (m^3/s)	Q_{weir} (m^3/s)	Q_m (m^3/s)
S38	0.740	2.196	0.206	0.201	0.2520	0.297	0.299	0.2980
S39	0.740	2.196	0.206	0.201	0.2750	0.400	0.396	0.3980
S40	0.740	2.196	0.305	0.101	0.1750	0.200	0.201	0.2005
S41	0.740	2.196	0.305	0.101	0.2090	0.299	0.301	0.3000
S42	0.740	2.196	0.305	0.101	0.1370	0.101	0.103	0.1020
S46	0.496	2.440	0.049	0.049	0.0930	0.101	0.102	0.1015
S47	0.496	2.440	0.049	0.049	0.1270	0.200	0.202	0.2010
S48	0.496	2.440	0.048	0.049	0.1500	0.301	0.300	0.3005
S49	0.495	2.438	0.101	0.050	0.0780	0.050	0.050	0.0500
S50	0.495	2.438	0.101	0.050	0.1370	0.201	0.205	0.2030
S51	0.495	2.438	0.101	0.050	0.1810	0.399	0.398	0.3985
S52	0.493	2.443	0.100	0.100	0.1340	0.100	0.101	0.1005
S53	0.493	2.443	0.100	0.100	0.1670	0.200	0.201	0.2005
S54	0.493	2.443	0.100	0.100	0.2150	0.401	0.396	0.3985
S55	0.495	2.442	0.099	0.200	0.2190	0.200	0.201	0.2005
S56	0.495	2.442	0.099	0.200	0.2510	0.300	0.301	0.3005
S57	0.495	2.442	0.099	0.200	0.2770	0.398	0.398	0.3980
S58	0.495	2.440	0.200	0.049	0.1070	0.101	0.101	0.1010
S59	0.495	2.440	0.200	0.049	0.1450	0.201	0.202	0.2015
S60	0.495	2.440	0.200	0.049	0.2020	0.398	0.396	0.3970
S61	0.495	2.442	0.201	0.100	0.1140	0.050	0.050	0.0500
S62	0.495	2.442	0.201	0.100	0.1800	0.200	0.202	0.2010
S63	0.495	2.442	0.201	0.100	0.2330	0.399	0.399	0.3990
S64	0.495	2.446	0.199	0.202	0.2380	0.200	0.201	0.2005
S64F	0.495	2.446	0.199	0.202	0.2390	0.199	0.203	0.2010
S65	0.495	2.446	0.199	0.202	0.2630	0.300	0.298	0.2990
S66	0.495	2.446	0.199	0.202	0.2920	0.399	0.400	0.3995

APPENDIX: B6

Thin-plate weir without dividing walls
University of Stellenbosch Tests

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_{meas} (m^3/s)	Q_{weir} (m^3/s)	Q_{m} (m^3/s)
S01	1.177	1.759	0.040	0.050	0.0680	0.050	0.052	0.0510
S02	1.177	1.759	0.040	0.050	0.1240	0.200	0.198	0.1990
S03	1.177	1.759	0.040	0.050	0.1510	0.298	0.299	0.2985
S04	1.177	1.759	0.091	0.050	0.0690	0.049	0.050	0.0495
S05	1.177	1.759	0.091	0.050	0.1310	0.200	0.203	0.2015
S06	1.177	1.759	0.091	0.050	0.1860	0.394	0.388	0.3910
S10	1.177	1.759	0.193	0.050	0.1360	0.201	0.200	0.2005
S11	1.177	1.759	0.193	0.050	0.1670	0.299	0.300	0.2995
S12	1.177	1.759	0.193	0.050	0.1960	0.402	0.392	0.3970
S13	1.174	1.761	0.193	0.100	0.1210	0.100	0.102	0.1010
S14	1.174	1.761	0.193	0.100	0.1640	0.200	0.203	0.2015
S15	1.174	1.761	0.193	0.100	0.2220	0.399	0.392	0.3955
S16	1.174	1.761	0.290	0.103	0.1670	0.200	0.204	0.2020
S17	1.174	1.761	0.290	0.103	0.2000	0.302	0.304	0.3030
S18	1.174	1.761	0.290	0.103	0.2290	0.400	0.399	0.3995
S19	0.740	2.192	0.050	0.050	0.0780	0.051	0.052	0.0515
S20	0.740	2.192	0.050	0.050	0.1370	0.201	0.201	0.2010
S21	0.740	2.192	0.050	0.050	0.1630	0.297	0.298	0.2975
S22H	0.739	2.196	0.101	0.050	0.0770	0.050	0.051	0.0505
S23H	0.739	2.196	0.101	0.050	0.1410	0.200	0.201	0.2005
S24H	0.739	2.196	0.101	0.050	0.1950	0.400	0.399	0.3995
S25	0.738	2.198	0.100	0.100	0.1390	0.100	0.103	0.1015
S26	0.738	2.198	0.100	0.100	0.1790	0.200	0.203	0.2015
S27	0.738	2.198	0.100	0.100	0.2350	0.399	0.398	0.3985
S28	0.736	2.197	0.099	0.199	0.2460	0.202	0.204	0.2030
S29	0.736	2.197	0.099	0.199	0.2790	0.301	0.300	0.3005
S30	0.736	2.197	0.099	0.199	0.3080	0.400	0.399	0.3995
S31	0.736	2.202	0.205	0.051	0.1050	0.098	0.100	0.0990
S32	0.736	2.202	0.205	0.051	0.1460	0.200	0.200	0.2000
S33	0.736	2.202	0.205	0.051	0.2050	0.399	0.399	0.3990
S34	0.740	2.196	0.205	0.100	0.1400	0.101	0.104	0.1025
S35	0.740	2.196	0.205	0.100	0.1810	0.199	0.201	0.2000
S36	0.740	2.196	0.205	0.100	0.2400	0.399	0.396	0.3975
S37	0.740	2.196	0.206	0.201	0.2450	0.197	0.200	0.1985

Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_{man} (m^3/s)	Q_{weir} (m^3/s)	Q_m (m^3/s)
S38	0.740	2.196	0.206	0.201	0.2820	0.301	0.300	0.3005
S39	0.740	2.196	0.206	0.201	0.3120	0.398	0.397	0.3975
S40	0.740	2.196	0.306	0.101	0.1840	0.202	0.205	0.2035
S41	0.740	2.196	0.306	0.101	0.2170	0.302	0.300	0.3010
S42	0.740	2.196	0.306	0.101	0.1390	0.099	0.099	0.0990
S46	0.496	2.433	0.048	0.049	0.1060	0.101	0.102	0.1015
S47	0.496	2.433	0.048	0.049	0.1430	0.201	0.203	0.2020
S48	0.496	2.433	0.048	0.049	0.1690	0.301	0.300	0.3005
S49	0.495	2.438	0.101	0.050	0.0820	0.047	0.049	0.0480
S50	0.495	2.438	0.101	0.050	0.1460	0.202	0.204	0.2030
S51	0.495	2.438	0.101	0.050	0.2020	0.398	0.395	0.3965
S52	0.495	2.437	0.101	0.101	0.1470	0.101	0.102	0.1015
S53	0.495	2.437	0.101	0.101	0.1890	0.201	0.203	0.2020
S54	0.495	2.437	0.101	0.101	0.2460	0.399	0.397	0.3980
S55	0.494	2.446	0.099	0.201	0.2650	0.200	0.202	0.2010
S56	0.494	2.446	0.099	0.201	0.3000	0.300	0.302	0.3010
S57	0.494	2.466	0.099	0.201	0.3280	0.400	0.400	0.4000
S58	0.494	2.438	0.200	0.049	0.1100	0.101	0.102	0.1015
S59	0.494	2.438	0.200	0.049	0.1500	0.200	0.202	0.2010
S60	0.494	2.438	0.200	0.049	0.2090	0.399	0.399	0.3990
S61	0.494	2.438	0.200	0.100	0.1200	0.050	0.050	0.0500
S62	0.494	2.438	0.200	0.100	0.1910	0.202	0.203	0.2025
S63	0.494	2.438	0.200	0.100	0.2510	0.399	0.400	0.3995
S64	0.495	2.434	0.199	0.201	0.2670	0.199	0.201	0.2000
S65	0.495	2.434	0.199	0.201	0.3040	0.300	0.301	0.3005
S66	0.495	2.434	0.199	0.201	0.3330	0.399	0.400	0.3995

APPENDIX C

APPENDIX: C1

Crump weir with dividing walls - test WMOD1-1s: flow confined to low notch. Total data set in Appendix D2.

l_1 = 1,597 m l_2 = 2,408 m   P = 0,269 m   t = 0,097 m

Q_m = 0,050 m³/s h_x = 0,0633 m

The general formula,

$$Q = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_d l H^{1,5} \text{ and } C_d = 1{,}163\left(1 - \frac{0{,}0003}{h}\right)^{1,5}$$

Determination of H_x and Q_{cx}

Low crest

$$Q_1 = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_{d1} l_1 H_x^{1,5} \text{ and } C_{d1} = 1{,}163\left(1 - \frac{0{,}0003}{h_x}\right)^{1,5}$$

First Iteration

Assume approach velocity in front of low notch, v_1, = 0 m/s initially.

$\Rightarrow H_x = h_x$ =0,0633 m

$$\therefore C_{d1} = 1{,}163\left(1 - \frac{0{,}0003}{0{,}0633}\right)^{1,5} = 1{,}1547$$

$$\text{and, } Q_1 = \left(\frac{2}{3}\right)^{1,5}\sqrt{g} \times 1{,}1547 \times 1{,}597 \times 0{,}0633^{1,5} = 0{,}0501 m^3/s$$

$$v_1 = \frac{Q_1}{A_1} = \frac{Q_1}{l_1 \times (P + h_x)} = \frac{0{,}0501}{1{,}597(0{,}269 + 0{,}0633)} = 0{,}0944 \text{ m/s}$$

$$\therefore H_x = h_x + \frac{v_1^2}{2g} = 0{,}0633 + \frac{(0{,}0944)^2}{2g} = 0{,}0638\text{m}$$

Second Iteration

Repeat with $H_x = 0{,}0638$m

$$Q_1 = \left(\frac{2}{3}\right)^{1,5} \times \sqrt{g} \times 1{,}1547 \times 1{,}597 \times 0{,}0638^{1,5} = 0{,}0506\text{m}^3/\text{s}$$

$$v_1 = \frac{0{,}0506}{1{,}597 \times (0{,}269 + 0{,}0633)} = 0{,}0953\text{m}/\text{s}$$

$$H_x = 0{,}0633 + \frac{(0{,}0953)^2}{2g} = 0{,}0638\text{m}$$

Third and further iterations

If the second iteration gives a different H_x continue until H_x and Q_1 remain constant from one iteration to the next. In this case two iterations were sufficient. For the case where flow is confined to the low notch $Q_1 = Q_{cx}$.

$$\therefore H_x = 0{,}0638\text{m}$$

and, $Q_{cx} = 0{,}0506\text{m}^3/\text{s}$

APPENDIX: C2

Crump weir with dividing walls - test WMOD3-3s: flow over both crests. Total data set in Appendix D3.

$l_1 = 0{,}999$ m $\quad$ $l_2 = 3{,}005$ m $\quad$ P = 0,103 m $\quad$ t = 0,098 m

$Q_m = 0{,}120 \text{ m}^3/\text{s}$ $\quad$ $h_x = 0{,}1133$ m

The general formula.

$$Q = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_d l H^{1,5} \quad \text{and} \quad C_d = 1{,}163\left(1 - \frac{0{,}0003}{h}\right)^{1,5}$$

Determination of H_x and Q_{cx}

Low crest

$$Q_l = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_{dl} l_l H_x^{1,5} \qquad \text{and} \qquad C_{dl} = 1{,}163\left(1 - \frac{0{,}0003}{h_x}\right)^{1,5}$$

First Iteration

Assume approach velocity in front of low notch, v_l, = 0 m/s initially.

$\Rightarrow H_x = h_x = 0{,}1133$ m

$$\therefore C_{dl} = 1{,}163\left(1 - \frac{0{,}0003}{0{,}1133}\right)^{1,5} = 1{,}1584$$

$$\text{and, } Q_l = \left(\frac{2}{3}\right)^{1,5}\sqrt{g} \times 1{,}1584 \times 0{,}999 \times 0{,}1133^{1,5} = 0{,}0752 \text{ m}^3/\text{s}$$

$$v_l = \frac{Q_l}{A_l} = \frac{Q_l}{l_l \times (P + h_x)} = \frac{0{,}0752}{0{,}999(0{,}103 + 0{,}1133)} = 0{,}3482 \text{ m/s}$$

$$\therefore H_x = h_x + \frac{v_1^2}{2g} = 0{,}1133 + \frac{(0{,}3482)^2}{2g} = 0{,}1195\text{m}$$

Second Iteration

Repeat with $H_x = 0{,}1195$m

$$Q_1 = \left(\frac{2}{3}\right)^{1,5} \times \sqrt{g} \times 1{,}1584 \times 0{,}999 \times 0{,}1195^{1,5} = 0{,}0815\text{m}^3/\text{s}$$

$$v_1 = \frac{0{,}0815}{0{,}999 \times (0{,}103 + 0{,}1133)} = 0{,}3771\text{m/s}$$

$$H_x = 0{,}1133 + \frac{(0{,}3771)^2}{2g} = 0{,}1205\text{m}$$

Third and further iterations

Continue until H_x and Q_1 remain constant from one iteration to the next. After the final interation :

$H_x = 0{,}1208$m

and, $Q_1 = 0{,}0829\text{m}^3/\text{s}$

High crest

Assuming a horizontal energy line across the width of the weir implies :

$H_2 = H_x - t$

$$\therefore Q_2 = \left(\frac{2}{3}\right)^{1,5} \sqrt{g} \times 1{,}163\left(1 - \frac{0{,}0003}{h_2}\right)^{1,5} l_2(H_x - t)^{1,5}$$

Furthermore, the assumption was made that the water level in front of the high notch;

$h_2 = H_x - t$

$$\therefore Q_2 = \left(\frac{2}{3}\right)^{1,5}\sqrt{g} \times 1,163\left(1 - \frac{0,0003}{0,1208 - 0,098}\right)^{1,5} \times 3,005 \times (0,1208 - 0,098)^{1,5} = 0,0201 m^3/s$$

Determination of Q_{cx}

$Q_{cx} = Q_1 + Q_2$

$= 0,0829 + 0,0201 = 0,103 m^3/s$

APPENDIX: C3

Crump weir with dividing walls - test WMOD3-3s: flow over both crests, improved calculation technique. Total data set in Appendix D3.

Determination of Q_{ck}

$$Q_{ck} = Q_1 + Q_2$$

$Q_1 = 0{,}0829\text{m}^3/\text{s}$ as determined in **Appendix: C2**

$$Q_{ck} = Q_1 + \left(\frac{2}{3}\right)^{1.5}\sqrt{g}\,1{,}163\left(1 - \frac{0{,}0003}{H_s - t}\right)^{1.5} l_2\left(H_s - t + \left(k_m\left(\frac{v_1^2}{2g}\right)\right)\right)^{1.5}$$

While for test WMOD3-3: $\frac{H_s}{t} = 1{,}233$; $\frac{l_2}{l_1} = 3{,}008$ and $\frac{t}{P} = 0{,}951$

$$\Rightarrow k_m = -1{,}6465\frac{H_s}{t} + 3{,}1560$$

$$k_m = -1{,}6465\frac{0{,}1208}{0{,}098} + 3{,}1560 = 1{,}1264$$

$$\therefore Q_{ck} = 0{,}0829 + \left(\frac{2}{3}\right)^{1.5}\sqrt{g}\,1{,}163\left(1 - \frac{0{,}0003}{0{,}1208 - 0{,}098}\right)^{1.5}$$
$$\times 3{,}005(0{,}1208 - 0{,}098 + (1{,}1264 \times 0{,}0075))^{1.5}$$

$$Q_{ck} = 0{,}0829 + 0{,}0323 = 0{,}115\text{m}^3/\text{s}$$

APPENDIX: C4

Thin-plate weir with dividing walls - test S20: flow over both crests, IMFT discharge formula. Total data set in Appendix D4.

$l_1 = 0{,}735$ m $\quad l_2 = 2{,}196$ m $\quad P = 0{,}050$ m $\quad t = 0{,}050$ m

$Q_m = 0{,}202\ m^3/s \quad h_s = 0{,}1207$ m

The general formula.

$$Q = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{H}{P}\right)lH^{3/2}$$

Determination of H_s and Q_{cs}

Low crest

$$Q_1 = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{H_s}{P}\right)l_1H_s^{3/2}$$

First Iteration

Assume approach velocity in front of the low notch, v_1, = 0 m/s initially.

$\Rightarrow H_s = h_s = 0{,}1207$ m

$$\therefore Q_1 = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{0{,}1207}{0{,}050}\right)\times 0{,}735\times(0{,}1207)^{3/2} = 0{,}0610\,m^3/s$$

$$v_1 = \frac{Q_1}{A_1} = \frac{Q_1}{l_1\times(P+h_s)} = \frac{0{,}0610}{0{,}735(0{,}050+0{,}1207)} = 0{,}4862\ m/s$$

$$\therefore H_s = h_s + \frac{v_1^2}{2g} = 0{,}1207 + \frac{(0{,}4862)^2}{2g} = 0{,}1327\,m$$

Second Iteration

Repeat with $H_x = 0{,}1327$m

$$Q_1 = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{0{,}1327}{0{,}050}\right) \times 0{,}735 \times (0{,}1327)^{3/2} = 0{,}0708\text{m}^3/\text{s}$$

$$v_1 = \frac{Q_1}{A} = \frac{Q_1}{l_1 \times (P + h_x)} = \frac{0{,}0708}{0{,}735(0{,}050 + 0{,}1207)} = 0{,}5643\,\text{m/s}$$

$$H_x = 0{,}1207 + \frac{(0{,}5643)^2}{2g} = 0{,}1369\text{m}$$

Third and further iterations

Continue until H_x and Q_1 remain constant from one iteration to the next. After the final iteration :

$H_x = 0{,}1398$m

and, $Q_1 = 0{,}0769\text{m}^3/\text{s}$

High crest

Assuming a horizontal energy line in front of the weir implies :

$H_2 = H_x - t$

$$Q_2 = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{H_x - t}{P + t}\right) l_2 (H_x - t)^{3/2}$$

$$\therefore Q_2 = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\left(\frac{0{,}1398 - 0{,}050}{0{,}050 + 0{,}050}\right)\right) \times 2{,}196 \times (0{,}1398 - 0{,}050)^{3/2} = 0{,}1122\text{m}^3/\text{s}$$

Determination of Q_{cx}

$Q_{cx} = Q_1 + Q_2$

$= 0{,}0769 + 0{,}1122 = 0{,}189 m^3/s$

APPENDIX: C5

Thin-plate weir with dividing walls - test S20: flow over both crests, improved calculation technique using IMFT discharge formula. Total data set in Appendix D4.

Determination of Q_{ck}

$$Q_{ck} = Q_1 + Q_2$$

$Q_1 = 0{,}0769 m^3/s$ as determined in **Appendix C4**

$$Q_{ck} = Q_1 + \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\left(\frac{H_s - t + k_m\left(\frac{v_s^2}{2g}\right)}{P + t}\right)\right) l_2 \left(H_s - t + k_m\left(\frac{v_s^2}{2g}\right)\right)^{3/2}$$

While for test S20: $\frac{H_s}{t} = 2{,}797$

$$\Rightarrow k_m = -0{,}1670\frac{H_s}{t} + 0{,}7014$$

$$k_m = -0{,}1670\frac{0{,}1398}{0{,}050} + 0{,}7014 = 0{,}2345$$

$$\therefore Q_{ck} = 0{,}0769 + \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\left(\frac{0{,}1398 - 0{,}050 + (0{,}2345 \times 0{,}0191)}{0{,}050 + 0{,}050}\right)\right)$$
$$\times 2{,}196 \times (0{,}1398 - 0{,}050 + (0{,}2345 \times 0{,}0191))^{3/2}$$

$$Q_{ck} = 0{,}0769 + 0{,}1209 = 0{,}198 m^3/s$$

APPENDIX: C6

Thin-plate weir with dividing walls - test S20: flow over both crests, DWAF discharge formula. Total data set in Appendix D5.

$l_1 = 0{,}735$ m $\quad$ $l_2 = 2{,}196$ m $\quad$ P = 0,050 m $\quad$ t = 0,050 m

$Q_m = 0{,}202$ m^3/s $\quad$ $h_x = 0{,}1207$ m

The general formula,

$$Q = 1{,}777\ l\ C_P\ (H + 0{,}001)^{3/2}$$

with,

$$C_P = 1{,}090 + 0{,}11\left(\frac{H}{H+P}\right)^{1{,}24} \qquad \text{if} \qquad H/P \leq 3{,}4$$

$$C_P = 1{,}145\left(\frac{P}{H+P}\right)^{0{,}09} \qquad \text{if} \qquad 3{,}4 < H/P \leq 200$$

$$C_P = 0{,}926 \qquad \text{if} \qquad H/P > 200$$

Determination of H_x and Q_{cx}

Low crest

$$Q_1 = 1{,}777\ l_1\ C_{P1}\ (H_x + 0{,}001)^{3/2}$$

First Iteration

Assume approach velocity in front of low notch, v_1, = 0 m/s initially.

$\Rightarrow H_x = h_x = 0{,}1207$ m

and, $\frac{H_x}{P} = \frac{0,1207}{0,050} = 2,414 < 3,4$

$$\Rightarrow C_{P1} = 1,000 + 0,11\left(\frac{H_x}{H_x + P}\right)^{1,24} = 1,000 + 0,11\left(\frac{0,1207}{0,1207 + 0,05}\right)^{1,24} = 1,07157$$

$$\therefore Q_1 = 1,777 \times 0,735 \times 1,0716 \times (0,1207 + 0,001)^{1,5} = 0,0594\,m^3/s$$

$$v_1 = \frac{Q_1}{A} = \frac{Q_1}{l_1 \times (P + h_x)} = \frac{0,0594}{0,735(0,050 + 0,1207)} = 0,4736\,m/s$$

$$\therefore H_x = h_x + \frac{v_1^2}{2g} = 0,1207 + \frac{(0,4736)^2}{2g} = 0,1321m$$

Second Iteration

Repeat with $H_x = 0,1321m$

$$C_{P1} = 1,000 + 0,11\left(\frac{0,1321}{0,1321 + 0,05}\right)^{1,24} = 1,0739$$

and, $Q_1 = 1,777 \times 0,735 \times 1,0739 \times (0,1321 + 0,001)^{1,5} = 0,0681m^3/s$

$$v_1 = \frac{0,0681}{0,735 \times (0,050 + 0,1207)} = 0,5429m/s$$

$$H_x = 0,1207 + \frac{(0,5429)^2}{2g} = 0,1357m$$

Third and further iterations

Continue until H_x and Q_1 remain constant from one iteration to the next. After the final iteration :

$H_x = 0,1378m$

and, $Q_1 = 0,0726m^3/s$

High crest

Assuming a horizontal energy line in front of the weir implies :

$H_2 = H_x - t$

$Q_2 = 1{,}777\ l_2\ C_{P2}\ (H_x - t + 0{,}001)^{3/2}$

and, $\dfrac{H_x - t}{P + t} = \dfrac{0{,}1378 - 0{,}050}{0{,}050 + 0{,}050} = 0{,}878 < 3{,}4$

$$\Rightarrow C_{P2} = 1{,}000 + 0{,}11\left(\frac{H_x - t}{H_x - t + P + t}\right)^{1{,}24} = 1{,}000 + 0{,}11\left(\frac{0{,}1378 - 0{,}05}{0{,}1378 + 0{,}05}\right)^{1{,}24} = 1{,}0428$$

$\therefore Q_2 = 1{,}777 \times 2{,}196 \times 1{,}0428 \times (0{,}1378 - 0{,}050 + 0{,}001)^{1{,}5} = 0{,}1076 m^3/s$

Determination of Q_{cx}

$Q_{cx} = Q_1 + Q_2$

$= 0{,}0726 + 0{,}1076 = 0{,}180 m^3/s$

APPENDIX: C7

Thin-plate weir with dividing walls - test S20: flow over both crests, improved calculation technique employing DWAF discharge formula. Total data set in Appendix D5.

Determination of Q_{ck}

$$Q_{ck} = Q_1 + Q_2$$

$Q_1 = 0{,}0726\text{m}^3/\text{s}$ as determined in **Appendix C6**

$$Q_{ck} = Q_1 + 1{,}777 l_2 C_{p2}\left(H_s - t + k_m\left(\frac{v_1^2}{2g}\right) + 0{,}001\right)^{1,5}$$

While for test S20: $\dfrac{H_s}{t} = 2{,}756$

$$\Rightarrow k_m = -0{,}1599\frac{H_s}{t} + 0{,}9998$$

$$k_m = -0{,}1599 \times \frac{0{,}1378}{0{,}050} + 0{,}9998 = 0{,}5591$$

$$\text{and, } C_{p2} = 1{,}000 + 0{,}11\left(\frac{H_s - t + k_m\left(\dfrac{v_1^2}{2g}\right)}{H_s - t + k_m\left(\dfrac{v_1^2}{2g}\right) + P + t}\right)^{1,24}$$

$$1{,}000 + 0{,}11\left(\frac{0{,}1378 - 0{,}05 + 0{,}5591 \times 0{,}0171}{0{,}1378 - 0{,}05 + 0{,}5591 \times 0{,}0171 + 0{,}05 + 0{,}05}\right)^{1,24} = 1{,}0458$$

$$Q_{ck} = 0{,}0726 + 1{,}777 \times 2{,}196 \times 1{,}0458(0{,}1378 - 0{,}050 + 0{,}001 + (0{,}5591 \times 0{,}0171))^{1,5}$$

$$= 0{,}0726 + 0{,}1259 = 0{,}198\text{m}^3/\text{s}$$

APPENDIX: D1

Crump weir with dividing walls; flow confined to low notch, h > 0.06m. Calculated values using the Crump calibration formula and then corrected for systematic reading error x = 0,0029m in the stage measurements.

	PHYSICAL PARMETERS				MEASURED VALUES		CALCULATED VALUES				CORRECTED CALCULATED VALUES				
Test Number	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	H (m)	Q (m^3/s)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WMOD1-1s	1.597	2.408	0.269	0.097	0.0636	0.050	0.0641	0.051	0.661	1.020	0.0633	0.0638	0.051	0.657	1.013
WMOD1-1s	1.597	2.408	0.269	0.097	0.0858	0.080	0.0868	0.081	0.895	1.007	0.0855	0.0865	0.080	0.892	1.002
WMOD1-2s	1.597	2.408	0.176	0.097	0.0635	0.050	0.0644	0.051	0.664	1.028	0.0632	0.0641	0.051	0.661	1.021
WMOD1-2s	1.597	2.408	0.176	0.097	0.0853	0.080	0.0872	0.081	0.899	1.014	0.0850	0.0869	0.081	0.896	1.009
WMOD1-3s	1.597	2.408	0.085	0.097	0.0616	0.050	0.0640	0.051	0.660	1.018	0.0613	0.0637	0.051	0.657	1.011
WMOD1-3s	1.597	2.408	0.085	0.097	0.0829	0.080	0.0876	0.082	0.903	1.021	0.0826	0.0873	0.081	0.900	1.016
WMOD2-1s	1.230	2.773	0.268	0.098	0.0748	0.050	0.0755	0.050	0.771	1.006	0.0745	0.0752	0.050	0.768	1.000
WMOD2-2s	1.230	2.773	0.173	0.098	0.0742	0.050	0.0756	0.050	[illegible]	1.008	0.0739	0.0753	0.050	0.766	1.002
WMOD2-3s	1.230	2.773	0.089	0.098	0.0718	0.050	0.0750	0.050	0.766	0.996	0.0715	0.0747	0.049	0.762	0.990
WMOD3-1s	0.999	3.005	0.268	0.098	0.0850	0.050	0.0860	0.050	0.878	0.994	0.0847	0.0857	0.049	0.875	0.989
WMOD3-2s	0.999	3.005	0.185	0.098	0.0850	0.050	0.0868	0.050	0.885	1.007	0.0847	0.0865	0.050	0.882	1.002
WMOD3-3s	0.999	3.005	0.103	0.098	0.0800	0.050	0.0834	0.047	0.851	0.949	0.0797	0.0831	0.047	0.848	0.944
WMOD4-3s	0.804	3.200	0.103	0.098	0.0915	0.050	0.0962	0.047	0.981	0.946	0.0912	0.0958	0.047	0.978	0.941
WMOD5-2s	0.672	3.332	0.183	0.099	0.0627	0.020	0.0635	0.021	0.642	1.059	0.0624	0.0632	0.021	0.639	1.052
WMOD5-3s	0.672	3.332	0.093	0.099	0.0596	0.020	0.0616	0.020	0.622	1.010	0.0593	0.0613	0.020	0.619	1.003
WMOD6-2s	0.670	3.332	0.211	0.071	0.0616	0.020	0.0622	0.020	0.877	1.024	0.0613	0.0619	0.020	0.872	1.017
WMOD6-3s	0.670	3.332	0.121	0.071	0.0594	0.020	0.0608	0.020	0.856	0.987	0.0591	0.0605	0.020	0.851	0.980
C1	1.197	1.780	0.171	0.107	0.0755	0.049	0.0770	0.050	0.720	1.021	0.0752	0.0767	0.050	0.717	1.015
C2	1.197	1.780	0.171	0.107	0.0959	0.072	0.0986	0.073	0.922	1.010	0.0956	0.0983	0.073	0.919	1.006
									AVG	1.007				AVG	1.001
									STD	0.025				STD	0.025
									MAX	1.059				MAX	1.052
									MIN	0.946				MIN	0.941
									n	19				n	19

APPENDIX: D2

Crump weir with dividing walls; flows confined to the low notch, complete data set.

	PHYSICAL PARMETERS				MEASURED VALUES		CALCULATED VALUES				CORRECTED CALCULATED VALUES				
Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)	H (m)	Q_c (m^3/s)	H/t	Q_c/Q_m	h_c (m)	H_c (m)	Q_{cc} (m^3/s)	H_c/t	Q_{cc}/Q_m
WMOD1-1s	1.597	2.408	0.269	0.097	0.0345	0.020	0.0346	0.0201	0.357	1.0052	0.0342	0.0343	0.0198	0.354	0.9924
WMOD1-1s	1.597	2.408	0.269	0.097	0.0636	0.050	0.0641	0.0510	0.661	1.0198	0.0633	0.0638	0.0506	0.657	1.0127
WMOD1-1s	1.597	2.408	0.269	0.097	0.0858	0.080	0.0868	0.0806	0.895	1.0075	0.0855	0.0865	0.0802	0.892	1.0022
WMOD1-2s	1.597	2.408	0.176	0.097	0.0352	0.020	0.0354	0.0208	0.365	1.0408	0.0349	0.0351	0.0206	0.362	1.0277
WMOD1-2s	1.597	2.408	0.176	0.097	0.0635	0.050	0.0644	0.0514	0.664	1.0282	0.0632	0.0641	0.0510	0.661	1.0209
WMOD1-2s	1.597	2.408	0.176	0.097	0.0853	0.080	0.0872	0.0811	0.899	1.0143	0.0850	0.0869	0.0807	0.896	1.0090
WMOD1-3s	1.597	2.408	0.085	0.097	0.0360	0.020	0.0367	0.0219	0.378	1.0973	0.0357	0.0364	0.0217	0.375	1.0836
WMOD1-3s	1.597	2.408	0.085	0.097	0.0616	0.050	0.0640	0.0509	0.660	1.0181	0.0613	0.0637	0.0505	0.657	1.0106
WMOD1-3s	1.597	2.408	0.085	0.097	0.0829	0.080	0.0876	0.0817	0.903	1.0212	0.0826	0.0873	0.0812	0.900	1.0155
WMOD2-3s	1.230	2.773	0.089	0.098	0.0423	0.020	0.0432	0.0217	0.441	1.0840	0.0420	0.0429	0.0214	0.438	1.0724
WMOD2-3s	1.230	2.773	0.089	0.098	0.0718	0.050	0.0750	0.0498	0.766	0.9962	0.0715	0.0747	0.0495	0.762	0.9898
WMOD2-2s	1.230	2.773	0.173	0.098	0.0433	0.020	0.0436	0.0220	0.445	1.1005	0.0430	0.0434	0.0218	0.442	1.0892
WMOD2-2s	1.230	2.773	0.173	0.098	0.0742	0.050	0.0756	0.0504	0.771	1.0078	0.0739	0.0753	0.0501	0.768	1.0017
WMOD2-1s	1.230	2.773	0.268	0.098	0.0433	0.020	0.0435	0.0219	0.444	1.0936	0.0430	0.0432	0.0216	0.441	1.0825
WMOD2-1s	1.230	2.773	0.268	0.098	0.0748	0.050	0.0755	0.0503	0.771	1.0063	0.0745	0.0752	0.0500	0.768	1.0004
WMOD3-1s	0.999	3.005	0.268	0.098	0.0473	0.020	0.0475	0.0203	0.485	1.0160	0.0470	0.0472	0.0201	0.482	1.0065
WMOD3-1s	0.999	3.005	0.268	0.098	0.0850	0.050	0.0860	0.0497	0.878	0.9941	0.0847	0.0857	0.0494	0.875	0.9889
WMOD3-2s	0.999	3.005	0.185	0.098	0.0486	0.020	0.0490	0.0213	0.500	1.0651	0.0483	0.0487	0.0211	0.497	1.0554
WMOD3-2s	0.999	3.005	0.185	0.098	0.0850	0.050	0.0868	0.0504	0.885	1.0073	0.0847	0.0865	0.0501	0.882	1.0020
WMOD3-3s	0.999	3.005	0.103	0.098	0.0454	0.020	0.0463	0.0195	0.472	0.9764	0.0451	0.0460	0.0193	0.469	0.9668
WMOD3-3s	0.999	3.005	0.103	0.098	0.0800	0.050	0.0834	0.0475	0.851	0.9494	0.0797	0.0831	0.0472	0.848	0.9440

	PHYSICAL PARMETERS				MEASURED VALUES		CALCULATED VALUES				CORRECTED CALCULATED VALUES				
Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	h (m)	Q_m (m^3/s)	H (m)	Q_t (m^3/s)	H/t	Q_t/Q_m	h_c (m)	H_c (m)	Q_{tc} (m^3/s)	H_c/t	Q_{tc}/Q_m
WMOD4-2s	0.804	3.200	0.183	0.098	0.0228	0.005	0.0229	0.0054	0.233	1.0799	0.0225	0.0226	0.0053	0.230	1.0590
WMOD4-2s	0.804	3.200	0.183	0.098	0.0352	0.010	0.0354	0.0105	0.361	1.0474	0.0349	0.0351	0.0103	0.358	1.0343
WMOD4-2s	0.804	3.200	0.183	0.098	0.0452	0.015	0.0456	0.0153	0.465	1.0231	0.0449	0.0453	0.0152	0.462	1.0131
WMOD4-2s	0.804	3.200	0.183	0.098	0.0542	0.020	0.0548	0.0203	0.559	1.0134	0.0539	0.0545	0.0201	0.556	1.0051
WMOD4-3s	0.804	3.200	0.103	0.098	[illegible]	0.010	0.0342	0.0100	0.349	0.9956	0.0335	0.0339	0.0098	0.346	0.9825
WMOD4-3s	0.804	3.200	0.103	0.098	0.0523	0.020	0.0536	0.0196	0.546	0.9794	0.0520	0.0532	0.0194	0.543	0.9709
WMOD4-3s	0.804	3.200	0.103	0.098	0.0915	0.050	0.0962	0.0473	0.981	0.9461	0.0912	0.0958	0.0471	0.978	0.9413
WMOD5-2s	0.672	3.332	0.183	0.099	0.0245	0.005	0.0246	0.0050	0.248	1.0073	0.0242	0.0243	0.0049	0.245	0.9892
WMOD5-2s	0.672	3.332	0.183	0.099	0.0401	0.010	0.0404	0.0107	0.408	1.0682	0.0398	0.0401	0.0106	0.405	1.0564
WMOD5-2s	0.672	3.332	0.183	0.099	0.0520	0.015	0.0525	0.0159	0.530	1.0598	0.0517	0.0522	0.0158	0.527	1.0508
WMOD5-2s	0.672	3.332	0.183	0.099	0.0627	0.020	0.0635	0.0212	0.642	1.0594	0.0624	0.0632	0.0210	0.639	1.0519
WMOD5-3s	0.672	3.332	0.093	0.099	0.0251	0.005	0.0253	0.0053	0.256	1.0548	0.0248	0.0250	0.0052	0.253	1.0361
WMOD5-3s	0.672	3.332	0.093	0.099	0.0388	0.010	0.0395	0.0103	0.399	1.0337	0.0385	0.0392	0.0102	0.396	1.0217
WMOD5-3s	0.672	3.332	0.093	0.099	0.0496	0.015	0.0509	0.0152	0.514	1.0101	0.0493	0.0506	0.0150	0.511	1.0008
WMOD5-3s	0.672	3.332	0.093	0.099	0.0596	0.020	0.0616	0.0202	0.622	1.0104	0.0593	0.0613	0.0201	0.619	1.0026
WMOD6-3s	0.670	3.332	0.121	0.071	0.0379	0.010	0.0383	0.0099	0.540	0.9854	0.0376	0.0380	0.0097	0.536	0.9738
WMOD6-3s	0.670	3.332	0.121	0.071	0.0594	0.020	0.0608	0.0197	0.856	0.9873	0.0591	0.0605	0.0196	0.851	0.9798
WMOD6-2s	0.670	3.332	0.211	0.071	0.0418	0.011	0.0420	0.0113	0.592	1.0294	0.0415	0.0417	0.0112	0.588	1.0185
WMOD6-2s	0.670	3.332	0.211	0.071	0.0616	0.020	0.0622	0.0205	0.877	1.0239	0.0613	0.0619	0.0203	0.872	1.0165
C1	1.197	1.780	0.171	0.107	0.0755	0.049	0.0770	0.0504	0.720	1.0206	0.0752	0.0767	0.0501	0.717	1.0145
C2	1.197	1.780	0.171	0.107	0.0959	0.072	0.0986	0.0731	0.922	1.0104	0.0956	0.0983	0.0728	0.919	1.0056
									AVG	1.0237				AVG	1.0143
									STD	0.0361				STD	0.0344
									MAX	1.1005				MAX	1.0892
									MIN	0.9461				MIN	0.9413
									N	42				N	42

APPENDIX: D3

Crump weir with dividing walls, flow over both crests

	PHYSICAL PARMETERS						MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
TEST NO.	l_1 (m)	l_2 (m)	P (m)	t (m)	t/P	l_2/l_1	Q_m (m^3/s)	h_c (m)	H_c (m)	Q_{sc} (m^3/s)	H_c/t	Q_{sc}/Q_m	k_{sc} Calc.	k_{sc} Fit	ΔH (m)	Q_{ic} (m^3/s)	Q_{ic}/Q_m
WMOD1 1s	1.597	2.408	0.269	0.097	0.361	1.508	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.986	1.175	0.506	0.0009	0.119	0.992
WMOD1 1s	1.597	2.408	0.269	0.097	0.361	1.508	[illegible]	[illegible]	[illegible]	[illegible]	1.248	[illegible]	0.138	0.458	0.0011	0.152	1.010
WMOD1 1s	1.597	2.408	0.269	0.097	0.361	1.508	0.177	0.1262	0.1289	0.173	1.329	0.977	1.145	0.429	0.0012	0.174	0.986
WMOD1 2s	1.597	2.408	0.176	0.097	0.551	1.508	0.120	0.1073	0.1107	0.123	1.141	1.029	-1.403	0.498	0.0017	0.125	1.030
WMOD1 2s	1.597	2.408	0.176	0.097	0.551	1.508	0.150	0.1174	0.1216	0.152	1.253	1.012	0.385	0.457	0.0019	0.154	1.026
WMOD1 2s	1.597	2.408	0.176	0.097	0.551	1.508	0.177	0.1265	0.1314	0.181	1.355	1.020	-0.551	0.419	0.0021	0.183	1.035
WMOD1 3s	1.597	2.408	0.085	0.097	1.141	1.508	0.120	0.1011	0.1084	0.119	1.118	0.984	0.331	0.506	0.0037	0.121	1.009
WMOD1 3s	1.597	2.408	0.085	0.097	1.141	1.508	0.150	0.1124	0.1216	0.152	1.253	1.012	-0.177	0.456	0.0042	0.157	1.044
WMOD1 3s	1.597	2.408	0.085	0.097	1.141	1.508	0.177	0.1211	0.1318	0.182	1.359	1.026	-0.339	0.418	0.0045	0.188	1.061
WMOD2 1s	1.230	2.773	0.268	0.098	0.366	2.254	0.080	0.0865	0.1010	0.079	1.031	0.984	1.786	0.538	0.0008	0.079	0.988
WMOD2 1s	1.230	2.773	0.268	0.098	0.366	2.254	0.120	0.1166	0.1192	0.117	1.216	0.971	1.251	0.470	0.0011	0.118	0.982
WMOD2 1s	1.230	2.773	0.268	0.098	0.366	2.254	0.150	0.1280	0.1384	0.147	1.335	0.982	0.629	0.426	0.0012	0.149	0.994
WMOD2 1s	1.230	2.773	0.268	0.098	0.366	2.254	0.177	0.1362	0.1395	0.173	1.424	0.976	0.772	0.394	0.0013	0.175	0.988
WMOD2 2s	1.230	2.773	0.173	0.098	0.566	2.254	0.080	0.0992	0.1021	0.080	1.041	1.005	-0.338	0.534	0.0015	0.081	1.015
WMOD2 2s	1.230	2.773	0.173	0.098	0.566	2.254	0.120	0.1169	0.1211	0.121	1.236	1.011	0.263	0.463	0.0019	0.124	1.032
WMOD2 2s	1.230	2.773	0.173	0.098	0.566	2.254	0.150	0.1269	0.1320	0.151	1.347	1.004	0.073	0.422	0.0021	0.154	1.026
WMOD2 2s	1.230	2.773	0.173	0.098	0.566	2.254	0.177	0.1342	0.1400	0.174	1.429	0.984	0.293	0.392	0.0023	0.178	1.006
WMOD2 3s	1.230	2.773	0.089	0.098	1.101	2.254	0.080	0.0943	0.1003	0.078	1.023	0.969	0.896	0.541	0.0032	0.079	0.986
WMOD2 3s	1.230	2.773	0.089	0.098	1.101	2.254	0.120	0.1097	0.1180	0.114	1.204	0.947	0.640	0.475	0.0039	0.118	0.986
WMOD2 3s	1.230	2.773	0.089	0.098	1.101	2.254	0.150	0.1203	0.1304	0.146	1.330	0.973	0.270	0.428	0.0043	0.152	1.016
WMOD2 3s	1.230	2.773	0.089	0.098	1.101	2.254	0.177	0.1266	0.1378	0.168	1.406	0.946	0.503	0.400	0.0045	0.175	0.989
WMOD3 1s	0.999	3.005	0.268	0.098	0.366	3.008	0.080	0.1068	0.1086	0.077	1.108	0.961	1.826	0.513	0.0009	0.078	0.971
WMOD3 1s	0.999	3.005	0.268	0.098	0.366	3.008	0.120	0.1224	0.1250	0.113	1.275	0.943	1.802	0.448	0.0011	0.115	0.956
WMOD3 1s	0.999	3.005	0.268	0.098	0.366	3.008	0.150	0.1327	0.1358	0.142	1.386	0.947	1.439	0.408	0.0013	0.144	0.962
WMOD3 1s	0.999	3.005	0.268	0.098	0.366	3.008	0.177	0.1410	0.1446	0.168	1.476	0.949	1.283	0.375	0.0013	0.171	0.964
WMOD3 2s	0.999	3.005	0.185	0.098	0.530	3.008	0.080	0.1071	0.1102	0.080	1.125	0.999	0.017	0.504	0.0016	0.081	1.019
WMOD3 2s	0.999	3.005	0.185	0.098	0.530	3.008	0.120	0.1226	0.1269	0.118	1.295	0.984	0.300	0.441	0.0019	0.121	1.008
WMOD3 2s	0.999	3.005	0.185	0.098	0.530	3.008	0.150	0.1336	0.1382	0.149	1.410	0.993	0.116	0.399	0.0021	0.153	1.018
WMOD3 2s	0.999	3.005	0.185	0.098	0.530	3.008	0.177	0.1413	0.1473	0.176	1.503	0.996	0.068	0.365	0.0022	0.181	1.020
WMOD3 3s	0.999	3.005	0.093	0.098	0.951	3.008	0.080	0.0965	0.1040	0.069	1.061	0.859	2.265	1.408	0.0077	0.075	0.938
WMOD3 3s	0.999	3.005	0.093	0.098	0.951	3.008	0.120	0.1133	0.1208	0.103	1.233	0.858	1.541	1.126	0.0084	0.115	0.959
WMOD3 3s	0.999	3.005	0.093	0.098	0.951	3.008	0.150	0.1219	0.1307	0.128	1.334	0.853	1.444	0.960	0.0084	0.142	0.948
WMOD3 3s	0.999	3.005	0.093	0.098	0.951	3.008	0.177	0.1301	0.1402	0.155	1.431	0.874	1.140	0.800	0.0081	0.170	0.961
WMOD4 2s	0.804	3.208	0.183	0.098	0.536	3.980	0.050	0.0959	0.0983	0.049	1.003	0.979	11.45	0.548	0.0013	0.049	0.979
WMOD4 2s	0.804	3.208	0.183	0.098	0.536	3.980	0.080	0.1131	0.1167	0.079	1.191	0.988	0.180	0.479	0.0017	0.081	1.018
WMOD4 2s	0.804	3.208	0.183	0.098	0.536	3.980	0.120	0.1281	0.1329	0.118	1.357	0.983	0.245	0.419	0.0020	0.122	1.013
WMOD4 2s	0.804	3.208	0.183	0.098	0.536	3.980	0.150	0.1381	0.1439	0.148	1.468	0.989	0.132	0.378	0.0022	0.153	1.019
WMOD4 2s	0.804	3.208	0.183	0.098	0.536	3.980	0.177	0.1453	0.1518	0.172	1.549	0.974	0.322	0.348	0.0022	0.177	1.002
WMOD4 3s	0.804	3.208	0.093	0.098	0.951	3.980	0.080	0.1055	0.1119	0.070	1.142	0.869	1.322	1.276	0.0082	0.080	0.995
WMOD4 3s	0.804	3.208	0.093	0.098	0.951	3.980	0.120	0.1184	0.1267	0.102	1.292	0.847	1.277	1.028	0.0085	0.116	0.969
WMOD4 3s	0.804	3.208	0.093	0.098	0.951	3.980	0.150	0.1264	0.1365	0.127	1.393	0.849	1.174	0.863	0.0083	0.143	0.956
WMOD4 3s	0.804	3.208	0.093	0.098	0.951	3.980	0.177	0.1329	0.1435	0.147	1.464	0.861	1.057	0.746	0.0079	0.164	0.958

	PHYSICAL PARMETERS						MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
TEST NO.	l_1 (m)	l_2 (m)	P (m)	t (m)	t/P	l_2/l_1	Q_m (m^3/s)	h_e (m)	H_e (m)	Q_{cs} (m^3/s)	H_e/t	Q_{cs}/Q_m	k_m Calc.	k_m Fit	ΔH (m)	Q_{ch} (m^3/s)	Q_{ch}/Q_m
WMOD5-2s	0.672	3.332	0.183	0.099	0.541	4.958	0.050	0.1026	0.1055	0.049	1.065	0.973	0.605	0.525	0.0015	0.050	0.996
WMOD5-2s	0.672	3.332	0.183	0.099	0.541	4.958	0.080	0.1180	0.1220	0.079	1.232	0.989	0.144	0.464	0.0018	0.082	1.024
WMOD5-2s	0.672	3.332	0.183	0.099	0.541	4.958	0.120	0.1331	0.1384	0.119	1.398	0.995	0.056	0.404	0.0021	0.124	1.030
WMOD5-2s	0.672	3.332	0.183	0.099	0.541	4.958	0.150	0.1422	0.1484	0.148	1.499	0.985	0.172	0.367	0.0023	0.153	1.018
WMOD5-2s	0.672	3.332	0.183	0.099	0.541	4.958	0.177	0.1501	0.1571	0.174	1.587	0.985	0.156	0.334	0.0023	0.180	1.017
WMOD5-3s	0.672	3.332	0.093	0.099	1.065	4.958	0.050	0.0962	0.1021	0.044	1.031	0.885	1.369	1.458	0.0086	0.050	1.010
WMOD5-3s	0.672	3.332	0.093	0.099	1.065	4.958	0.080	0.1094	0.1172	0.069	1.184	0.864	0.973	1.206	0.0094	0.083	1.036
WMOD5-3s	0.672	3.332	0.093	0.099	1.065	4.958	0.120	0.1234	0.1335	0.107	1.349	0.888	0.695	0.935	0.0095	0.125	1.041
WMOD5-3s	0.672	3.332	0.093	0.099	1.065	4.958	0.150	0.1322	0.1439	0.135	1.454	0.898	0.605	0.763	0.0089	0.154	1.028
WMOD5-3s	0.672	3.332	0.093	0.099	1.065	4.958	0.174	0.1382	0.1510	0.156	1.526	0.895	0.613	0.644	0.0083	0.175	1.006
WMOD6-2s	0.670	3.332	0.211	0.071	0.336	4.973	0.050	0.0865	0.0880	[illegible]	[illegible]	[illegible]	0.600	0.461	[illegible]	0.050	0.995
WMOD6-2s	0.670	3.332	0.211	[illegible]	0.336	4.973	0.080	[illegible]	0.1018	0.078	1.434	0.976	0.507	0.390	0.0008	0.080	0.995
WMOD6-2s	0.670	3.332	0.211	0.071	0.336	4.973	0.120	0.1141	0.1171	0.118	1.650	0.982	0.332	0.311	0.0009	0.120	0.999
WMOD6-2s	0.670	3.332	0.211	0.071	0.336	4.973	0.150	0.1237	0.1274	0.148	1.794	0.986	0.242	0.258	0.0009	0.150	1.001
WMOD6-2s	0.670	3.332	0.211	0.071	0.336	4.973	0.175	0.1306	0.1348	0.171	1.898	0.978	0.365	0.220	0.0009	0.173	0.991
WMOD6-3s	0.670	3.332	0.121	0.071	0.587	4.973	0.050	0.0832	0.0863	0.046	1.215	0.911	1.159	0.471	0.0014	0.047	0.946
WMOD6-3s	0.670	3.332	0.121	0.071	0.587	4.973	0.080	0.0962	0.1005	0.075	1.415	0.938	0.677	0.397	0.0017	0.078	0.974
WMOD6-3s	0.670	3.332	0.121	0.071	0.587	4.973	0.120	0.1097	0.1155	0.113	1.626	0.943	0.562	0.320	0.0018	0.117	0.975
WMOD6-3s	0.670	3.332	0.121	0.071	0.587	4.973	0.150	0.1188	0.1257	0.143	1.770	0.952	0.455	0.267	0.0018	0.147	0.980
WMOD6-3s	0.670	3.332	0.121	0.071	0.587	4.973	0.175	0.1250	0.1327	0.164	1.869	0.940	0.552	0.231	0.0018	0.169	0.965
C3	1.197	1.780	0.171	0.107	0.625	1.487	0.121	0.1229	0.1277	0.118	1.195	0.976	0.770	0.478	0.0023	0.120	0.991
C4	1.197	1.780	0.171	0.107	0.625	1.487	0.15[illegible]	0.1350	0.1410	0.147	1.319	0.972	0.714	0.433	0.0026	0.150	0.989
C5	1.197	1.780	0.171	0.107	0.625	1.487	0.202	0.1533	0.1612	0.198	1.508	0.978	0.454	0.363	0.0029	0.201	0.996
C6	1.197	1.780	0.171	0.107	0.625	1.487	0.300	0.1831	0.1949	0.295	1.823	0.983	0.268	0.248	0.0029	0.300	0.999
C7	1.197	1.780	0.171	0.107	0.625	1.487	0.397	0.2077	0.2232	0.389	2.088	0.980	0.280	0.151	0.0023	0.393	0.991
C8	0.735	2.242	0.171	0.106	0.620	3.050	0.150	0.1520	0.1598	0.148	1.506	0.982	0.223	0.364	0.0028	0.152	1.011
C9	0.735	2.242	0.171	0.106	0.620	3.050	0.201	0.1705	0.1806	0.201	1.702	1.002	-0.020	0.292	0.0029	0.207	1.029
C10	0.735	2.242	0.171	0.106	0.620	3.050	0.300	0.1998	0.2140	0.301	2.017	1.002	0.017	0.177	0.0025	0.306	1.020
C11	0.735	2.242	0.171	0.106	0.620	3.050	0.396	0.2263	0.2449	0.405	2.308	1.023	0.196	0.070	0.0013	0.409	1.031
C12	0.479	2.498	0.171	0.107	0.625	5.215	0.200	0.1767	0.1876	0.190	1.753	0.946	0.466	0.273	0.0030	0.196	0.978
C13	0.479	2.498	0.171	0.107	0.626	5.215	0.299	0.2046	0.2196	0.284	2.052	0.948	0.414	0.164	0.0025	0.290	0.968
C14	0.479	2.498	0.171	0.107	0.626	5.215	0.398	0.2302	0.2495	0.384	2.331	0.965	0.260	0.062	0.0012	0.387	0.973
C15	0.479	2.498	0.089	0.107	1.208	5.215	0.071	0.1203	0.1304	0.062	1.220	0.878	0.712	1.147	0.0116	0.077	1.082
C16	0.479	2.498	0.089	0.107	1.208	5.215	0.102	0.1336	0.1462	0.091	1.368	0.897	0.545	0.904	0.0114	0.109	1.072
C17	0.479	2.498	0.089	0.107	1.208	5.215	0.202	0.1682	0.1885	0.192	1.763	0.953	0.218	0.270	0.0055	0.204	1.011
C18	0.479	2.498	0.089	0.107	1.208	5.215	0.299	0.1946	0.2217	0.291	2.074	0.973	0.120	0.156	0.0042	0.302	1.008
C19	0.479	2.498	0.089	0.107	1.208	5.215	0.399	0.2209	0.2558	0.406	2.393	1.019	0.078	0.039	0.0014	0.410	1.029
C20	0.735	2.242	0.089	0.107	1.208	3.050	0.081	0.1142	0.1233	0.072	1.153	0.891	1.030	1.257	0.0114	0.083	1.027
C21	0.735	2.242	0.089	0.107	1.208	3.050	0.121	0.1310	0.1431	0.109	1.339	0.898	0.767	0.952	0.0115	0.124	1.026
C22	0.735	2.242	0.089	0.107	1.208	3.050	0.201	0.1572	0.1749	0.184	1.636	0.917	0.533	0.463	0.0082	[illegible]	[illegible]
C23	0.735	2.242	0.089	0.107	1.208	3.050	0.299	0.1833	0.2074	0.278	1.940	0.931	0.395	0.265	[illegible]	[illegible]	[illegible]
C24	0.735	2.242	0.089	0.107	1.208	3.050	0.399	0.2070	0.237[illegible]	0.378	2.223	0.948	0.279	[illegible]	[illegible]	[illegible]	[illegible]
C25	1.197	1.780	0.089	0.107	1.201	1.487	0.151	0.1255	0.1365	0.137	1.277	0.905	1.304	0.448	[illegible]	0.142	[illegible]
C26	1.197	1.780	0.089	0.107	1.201	1.487	0.201	0.1446	0.1594	0.193	1.491	0.960	0.440	0.369	0.0055	0.199	0.993
C27	1.197	1.780	0.089	0.107	1.201	1.487	0.300	0.1745	0.1962	0.299	1.835	0.999	0.006	0.243	0.0053	0.308	1.027
C28	1.197	1.780	0.089	0.107	1.201	1.487	0.399	0.1986	0.2267	[illegible]	2.121	1.007	0.052	0.139	[illegible]	[illegible]	1.025

	Standard calculation technique	Improved calculation technique
AVE	0.957	1.000
STD	0.048	0.029
MAX	1.029	1.082
MIN	0.849	0.936
n	88	88

APPENDIX: D4

Sharp crested weir with dividing walls; flow over both crests. IMFT formula.

	PHYSICAL PARMETERS						MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
TEST NO.	l_1 (m)	l_2 (m)	P (m)	t (m)	t/P	l_2/l_1	Q_m (m³/s)	h_m (m)	H_c (m)	Q_{sc} (m³/s)	H/t	Q_{sc}/Q_m	k_m Calc.	k_m Fit	ΔH (m)	Q_{ic} (m³/s)	Q_{ic}/Q_m
S01	1.177	1.759	0.040	0.050	1.250	1.494	0.051	0.0597	0.0650	0.044	1.300	0.867	1.827	0.484	0.0026	0.045	0.899
S02	1.177	1.759	0.040	0.050	1.250	1.494	0.201	0.1107	0.1318	0.192	2.636	0.957	0.275	0.261	0.0055	0.201	0.998
S03	1.177	1.759	0.040	0.050	1.250	1.494	0.304	0.1347	0.1703	0.313	3.407	1.032	-0.152	0.132	0.0047	0.322	1.060
S04	1.177	1.759	0.091	0.050	0.549	1.494	0.054	0.0697	0.0724	0.054	1.448	1.007	-0.195	0.460	0.0012	0.055	1.024
S05	1.177	1.759	0.091	0.050	0.549	1.494	0.200	0.1257	0.1359	0.197	2.717	0.986	0.189	0.248	0.0025	0.201	1.004
S06	1.177	1.759	0.091	0.050	0.549	1.494	0.396	0.1737	0.1943	0.382	3.886	0.964	0.347	0.052	0.0011	0.384	0.970
S10	1.177	1.759	0.193	0.050	0.259	1.494	0.204	0.1327	0.1371	0.198	2.743	0.971	0.907	0.243	0.0011	0.199	0.979
S11	1.177	1.759	0.193	0.050	0.259	1.494	0.299	0.1647	0.1720	[illegible]	3.440	1.006	-0.139	0.127	0.0009	0.302	1.011
S12	1.177	[illegible]	[illegible]	[illegible]	[illegible]	1.494	[illegible]	0.1927	[illegible]	[illegible]	[illegible]	1.018	[illegible]	0.023	0.0002	[illegible]	1.020
S13	1.174	1.761	0.193	0.100	0.518	1.500	0.103	0.1177	0.1210	0.103	1.210	1.001	-0.062	0.499	0.0017	0.104	1.013
S14	1.174	1.761	0.193	0.100	0.518	1.500	0.205	0.1597	0.1665	0.208	1.665	1.015	-0.368	0.423	0.0029	0.211	1.034
S15	1.174	1.761	0.193	0.100	0.518	1.500	0.397	0.2187	0.2326	0.412	[illegible]	1.037	-0.593	0.313	0.0043	0.420	1.057
S16	1.174	1.761	0.290	0.103	0.355	1.500	0.198	0.1607	0.1647	0.198	1.599	1.001	-0.061	0.434	0.0017	0.200	1.012
S17	1.174	1.761	0.290	0.103	0.355	1.500	0.301	0.1957	0.2021	0.304	1.962	1.009	0.283	0.374	0.0024	0.308	1.022
S18	1.174	1.761	0.290	0.103	0.355	1.500	[illegible]	0.2217	0.2302	0.395	2.235	0.995	0.136	0.328	0.0028	0.400	1.007
S19	0.735	2.196	0.050	0.050	1.000	2.988	[illegible]	0.0687	0.0742	0.044	1.484	0.857	1.300	0.628	0.0035	0.048	0.924
S20	0.735	2.196	0.050	0.050	1.000	2.988	0.202	0.1207	0.1398	0.189	2.797	0.937	0.344	0.234	0.0045	0.198	0.980
S21	0.735	2.196	0.050	0.050	1.000	2.988	0.300	0.1417	0.1697	0.279	3.394	0.930	0.329	0.135	0.0038	0.287	0.958
S22H	0.739	2.196	0.100	0.050	0.500	2.972	0.050	0.0727	0.0753	0.045	1.506	0.916	1.558	0.450	0.0012	0.047	0.940
S23H	0.739	2.196	0.100	0.050	0.500	2.972	0.201	[illegible]	0.1417	0.191	2.835	0.950	0.518	0.228	0.0023	0.195	0.972
S24H	0.739	2.196	0.100	0.050	0.500	2.972	0.397	0.1817	0.2020	0.379	4.041	0.956	0.341	0.027	0.0005	0.381	0.959
S25	0.738	2.198	0.100	0.100	1.000	2.978	0.100	0.1237	0.1325	0.092	1.325	0.923	0.760	0.822	0.0072	0.101	1.007
S26	0.738	2.198	0.100	0.100	1.000	2.978	0.201	0.1617	0.1775	0.196	1.775	0.975	0.180	0.405	0.0064	0.207	1.031
S27	0.738	2.198	0.100	0.100	1.000	2.978	0.401	0.2087	0.2363	0.376	2.363	0.940	0.369	0.307	0.0085	0.396	0.990
S28	0.735	2.203	0.100	0.199	1.990	2.997	0.201	0.1957	0.2196	0.161	1.104	0.803	1.399	1.091	0.0261	0.190	0.949
S29	0.735	2.203	0.100	0.199	1.990	2.997	0.301	0.2247	0.2572	0.248	1.293	0.825	0.964	0.861	0.0280	0.295	0.979
S30	0.735	2.203	0.100	0.199	1.990	2.997	0.398	0.2497	0.2911	0.347	1.463	0.871	0.618	0.654	0.0271	0.401	1.008
S31	0.736	2.202	0.205	0.051	0.249	2.992	0.101	0.1027	0.1049	0.098	2.057	0.978	0.691	0.358	0.0008	0.099	0.989
S32	0.736	2.202	0.205	0.051	0.249	2.992	0.202	0.1427	0.1475	0.202	2.893	1.002	0.049	0.218	0.0011	0.205	1.012
S33	0.736	2.202	0.205	0.051	0.249	2.992	0.398	0.2007	0.2113	0.403	4.144	1.012	-0.178	[illegible]	0.0001	0.403	1.013
S34	0.740	2.196	0.205	0.100	0.488	2.968	0.099	0.1307	0.1346	0.095	1.346	0.962	0.816	0.477	0.0019	0.097	0.984
S35	0.740	2.196	0.205	0.100	0.488	2.968	0.200	0.1727	0.1802	0.201	1.802	1.006	0.085	0.400	0.0030	0.206	1.032
S36	0.740	2.196	0.205	0.100	0.488	2.968	0.396	0.2237	0.2373	0.373	2.373	0.943	0.705	0.305	0.0041	0.383	0.968
S37	0.740	2.196	0.206	0.201	0.976	2.968	0.198	0.2207	0.2338	0.184	1.163	0.930	0.884	1.019	0.0133	0.200	1.012
S38	0.740	2.196	0.206	0.201	0.976	2.968	0.298	0.2517	0.2692	0.271	1.339	0.911	0.895	0.804	0.0141	0.295	[illegible]
S39	0.740	2.196	0.206	0.201	0.976	2.968	0.398	0.2747	[illegible]	0.349	1.472	0.878	1.131	0.642	[illegible]	0.376	0.946
S40	0.740	2.196	0.305	0.101	0.331	2.968	0.201	0.1747	0.1792	0.195	1.775	0.973	0.678	0.405	0.0018	0.198	0.989
S41	0.740	2.196	0.305	0.101	0.331	2.968	0.300	0.2087	0.2156	0.299	2.135	0.997	[illegible]	0.345	0.0024	0.304	1.013
S42	0.740	2.196	0.305	0.101	0.331	2.968	0.102	[illegible]	[illegible]	[illegible]	[illegible]	1.005	[illegible]	[illegible]	[illegible]	0.104	1.019

	PHYSICAL PARMETERS						MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
TEST NO.	s_1 (m)	l_2 (m)	P (m)	t (m)	t/P	l_2/l_1	Q_m	h_m (m)	H_0 (m)	Q_{sc}	H/t	Q_m/Q_{sc}	[illegible]	[illegible]	ΔH	[illegible]	Q_m/Q_c
S46	0.496	2.440	0.049	0.049	1.000	4.919	0.102	0.0927	0.1036	0.091	2.114	0.897	0.575	0.348	0.0038	0.097	0.959
S47	0.496	2.440	0.049	0.049	1.000	4.919	0.201	0.1267	0.1487	0.204	3.035	1.013	-0.053	0.195	0.0043	0.213	1.061
S48	0.496	2.440	0.048	0.049	1.021	4.919	0.301	0.1497	0.1841	0.314	3.756	1.044	-0.146	0.074	0.0025	0.320	1.066
S49	0.495	2.438	0.101	0.050	0.495	4.925	0.050	0.0777	0.0807	0.046	1.614	0.919	1.093	0.432	0.0013	0.048	0.950
S50	0.495	2.438	0.101	0.050	0.495	4.925	0.203	0.1367	0.1475	0.194	2.950	0.956	0.379	0.209	0.0022	0.199	0.980
S51	0.495	2.438	0.101	0.050	0.495	4.925	0.399	0.1807	0.2006	0.358	4.011	0.899	0.719	0.032	0.0006	0.360	0.903
S52	0.493	2.443	0.100	0.100	1.000	4.955	0.101	0.1337	0.1441	0.094	1.441	0.937	0.416	0.681	0.0071	0.105	1.042
S53	0.493	2.443	0.100	0.100	1.000	4.955	0.201	0.1667	0.1835	0.186	1.835	0.928	0.419	0.395	0.0066	0.200	0.996
S54	0.493	2.443	0.100	0.100	1.000	4.955	0.399	0.2147	0.2441	0.370	2.441	0.929	0.354	0.294	0.0086	0.394	0.988
S55	0.495	2.442	0.099	0.200	2.020	4.933	0.202	0.2187	0.2497	0.173	1.249	0.858	0.557	0.915	0.0284	0.222	1.102
S56	0.495	2.442	0.099	0.200	2.020	4.933	0.301	0.2507	0.2930	0.287	1.465	0.956	0.148	0.651	0.0275	0.349	1.162
S57	0.495	2.442	0.099	0.200	2.020	4.933	0.39	0.2767	0.3302	0.406	1.651	1.019	-0.058	0.426	0.0228	0.465	1.169
S58	0.495	2.440	0.200	0.049	0.245	4.929	0.101	0.106	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.32	[illegible]	0.102	1.012
S59	0.495	2.440	0.200	0.049	0.245	4.929	0.202	0.1447	0.1499	0.201	3.059	0.996	0.066	0.191	0.0010	0.203	1.007
S60	0.495	2.440	0.200	0.049	0.245	4.929	0.397	0.2017	0.2128	0.398	4.343	1.002	-0.026	-0.024	-0.000	0.397	1.000
S61	0.495	2.442	0.201	0.100	0.498	4.933	0.050	0.1137	0.1166	0.047	1.166	0.936	1.208	0.507	0.0015	0.048	0.962
S62	0.495	2.442	0.201	0.100	0.498	4.933	0.201	0.1797	0.1882	0.196	1.882	0.976	0.275	0.387	0.0033	0.203	1.010
S63	0.495	2.442	0.201	0.100	0.498	4.933	0.399	0.2327	0.2479	0.378	2.479	0.947	0.515	0.287	0.0044	0.390	0.976
S64	0.495	2.446	0.199	0.202	1.015	4.941	0.201	0.2377	0.2538	0.175	1.256	0.871	0.967	0.905	0.0146	0.199	0.991
S64F	0.495	2.446	0.199	0.202	1.015	4.941	0.201	0.2387	0.2549	0.178	1.262	0.884	0.857	0.898	0.0146	0.202	1.006
S65	0.495	2.446	0.199	0.202	1.015	4.941	0.299	0.2627	0.2828	0.248	1.400	0.829	1.214	0.731	0.0147	0.278	0.929
S66	0.495	2.446	0.199	0.202	1.015	4.941	0.400	0.2917	0.3170	0.349	1.569	0.874	0.819	0.524	0.0132	0.381	0.953
											AVE	0.951				AVE	1.000
											STD	0.057				STD	0.049
											MAX	1.044				MAX	1.169
											MIN	0.803				MIN	0.899
											n	61				n	61

APPENDIX: D5

Sharp crested weir with dividing walls; flow over both crests. DWAF formula.

	PHYSICAL PARMETERS						MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
TEST NO.	b_1 (m)	b_2 (m)	P (m)	t (m)	t/P	b_2/b_1	Q_m (m^3/s)	h_m (m)	H_e (m)	Q_{cs} (m^3/s)	H/t	Q_{cs}/Q_m	h_m Calc.	h_m ?	ΔH (m)	Q_{ci} (m^3/s)	Q_{ci}/Q_m
S01	1.177	1.759	0.040	0.050	1.250	1.494	0.051	0.0597	0.0649	0.044	1.298	0.869	1.835	0.792	0.004	0.046	0.921
S02	1.177	1.759	0.040	0.050	1.250	1.494	0.201	0.1107	0.1287	0.179	2.574	0.889	0.839	0.588	0.011	0.194	0.966
S03	1.177	1.759	0.040	0.050	1.250	1.494	0.304	0.1347	0.1601	0.267	3.202	0.880	0.813	0.488	0.012	0.288	0.950
S04	1.177	1.759	0.091	0.050	0.549	1.494	0.054	0.0697	0.0724	0.055	1.448	1.009	0.267	0.768	0.002	0.056	1.039
S05	1.177	1.759	0.091	0.050	0.549	1.494	0.200	0.1257	0.1355	0.194	2.710	0.969	0.441	0.566	0.006	0.202	1.010
S06	1.177	1.759	0.091	0.050	0.549	1.494	0.396	0.1737	0.1928	0.369	3.856	0.932	0.726	0.440	0.008	0.385	0.973
S10	1.177	1.759	0.193	0.050	0.259	1.494	0.204	0.1327	0.1370	0.195	2.740	0.956	1.424	0.562	0.002	0.198	0.973
S11	1.177	1.759	0.193	0.050	0.259	1.494	0.299	0.1647	0.1718	0.295	3.436	0.988	0.286	0.450	0.003	0.301	1.007
S12	1.177	1.759	0.193	0.050	0.259	1.494	0.397	0.1927	0.2028	0.397	4.056	0.999	0.023	0.440	0.004	0.405	1.021
S13	1.174	1.761	0.193	0.100	0.518	1.500	0.103	0.1177	0.1209	0.102	1.209	0.992	0.356	0.806	0.003	0.104	1.008
S14	1.174	1.761	0.193	0.100	0.518	1.500	0.205	0.1597	0.1663	0.204	1.663	1.000	0.017	0.734	0.005	0.210	1.028
S15	1.174	1.761	0.193	0.100	0.518	1.500	0.397	0.2187	0.2320	0.403	2.320	1.015	-0.249	0.629	0.008	0.418	1.052
S16	1.174	1.761	0.290	0.103	0.355	1.500	0.198	0.1607	0.1645	0.194	1.597	0.984	0.702	0.744	0.003	0.198	1.000
S17	1.174	1.761	0.290	0.103	0.355	1.500	0.301	0.1957	0.2018	0.298	1.959	0.989	0.354	0.687	0.004	0.304	1.010
S18	1.174	1.761	0.290	0.103	0.355	1.500	0.397	0.2217	0.2299	0.387	2.232	0.974	0.727	0.643	0.005	0.396	0.997
S19	0.735	2.196	0.050	0.050	1.000	2.988	0.052	0.0687	0.0741	0.044	1.482	0.858	1.317	0.909	0.005	0.049	0.9528
S20	0.735	2.196	0.050	0.050	1.000	2.988	0.202	0.1207	0.1378	0.180	2.756	0.892	0.669	0.559	0.010	0.198	0.983
S21	0.735	2.196	0.050	0.050	1.000	2.988	0.300	0.1417	0.1651	0.258	3.302	0.860	0.808	0.472	0.011	0.282	0.941
S22H	0.739	2.196	0.100	0.050	0.500	2.972	0.050	0.0727	0.0753	0.046	1.506	0.919	1.531	0.759	0.002	0.047	0.959
S23H	0.739	2.196	0.100	0.050	0.500	2.972	0.201	0.1317	0.1414	0.188	2.828	0.934	0.723	0.548	0.005	0.198	0.984
S24H	0.739	2.196	0.100	0.050	0.500	2.972	0.397	0.1817	0.2006	0.368	4.012	0.927	0.620	0.440	0.008	0.388	0.978
S25	0.738	2.198	0.100	0.100	1.000	2.978	0.100	0.1237	0.1322	0.091	1.322	0.910	0.927	1.133	0.010	0.102	1.0228
S26	0.738	2.198	0.100	0.100	1.000	2.978	0.201	0.1617	0.1766	0.191	1.766	0.948	0.405	0.717	0.011	0.209	1.042
S27	0.738	2.198	0.100	0.100	1.000	2.978	0.401	0.2087	0.2338	0.360	2.338	0.898	0.694	0.626	0.016	0.397	0.990
S28	0.735	2.203	0.100	0.199	1.990	2.997	0.201	0.1957	0.2177	0.154	1.094	0.766	1.816	1.452	0.032	0.189	0.9435
S29	0.735	2.203	0.100	0.199	1.990	2.997	0.301	0.2247	0.2538	0.232	1.275	0.772	1.425	1.198	0.035	0.289	0.9601
S30	0.735	2.203	0.100	0.199	1.990	2.997	0.398	0.2497	0.2855	0.319	1.435	0.801	1.114	0.975	0.035	0.387	0.9726
S31	0.736	2.202	0.205	0.051	0.249	2.992	0.101	0.1027	0.1048	0.097	2.055	0.964	1.183	0.671	0.001	0.099	0.986
S32	0.736	2.202	0.205	0.051	0.249	2.992	0.202	0.1427	0.1474	0.199	2.890	0.984	0.368	0.538	0.003	0.204	1.010
S33	0.736	2.202	0.205	0.051	0.249	2.992	0.398	0.2007	0.2109	0.394	4.135	0.990	0.150	0.440	0.004	0.406	1.020
S34	0.740	2.196	0.205	0.100	0.488	2.968	0.099	0.1307	0.1345	0.094	1.345	0.952	1.102	0.785	0.003	0.098	0.985
S35	0.740	2.196	0.205	0.100	0.488	2.968	0.200	0.1727	0.1800	0.197	1.800	0.987	0.206	0.712	0.005	0.206	1.033
S36	0.740	2.196	0.205	0.100	0.488	2.968	0.396	0.2237	0.2367	0.365	2.367	0.922	1.026	0.621	0.008	0.383	0.969
S37	0.740	2.196	0.206	0.201	0.976	2.968	0.198	0.2207	0.2332	0.180	1.160	0.911	1.186	1.359	0.017	0.201	1.0136
S38	0.740	2.196	0.206	0.201	0.976	2.968	0.298	0.2517	0.2684	0.264	1.335	0.887	1.206	1.114	0.019	0.295	0.9908
S39	0.740	2.196	0.206	0.201	0.976	2.968	0.398	0.2747	0.2949	0.339	1.467	0.853	1.466	0.930	0.019	0.376	0.9441
S40	0.740	2.196	0.305	0.101	0.331	2.968	0.201	0.1747	0.1791	0.191	1.773	0.955	1.221	0.716	0.003	0.197	0.982

	PHYSICAL PARMETERS						MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
TEST NO.	l_1 (m)	l_2 (m)	P (m)	t (m)	t/P	l_2/l_1	Q_m (m³/s)	h_m (m)	H_c (m)	Q_c (m³/s)	H/t	Q_c/Q_m	[illegible]	[illegible]	ΔH (m)	Q_c [illegible]	Q_c/Q_m
S41	0.740	2.196	0.305	0.101	0.331	2.968	0.300	0.2087	0.2153	0.293	2.132	0.975	0.538	0.659	0.004	0.301	1.005
S42	0.740	2.196	0.305	0.101	0.331	2.968	0.102	0.1367	0.1391	0.101	1.377	0.991	0.326	0.780	0.002	0.103	1.013
S46	0.496	2.440	0.049	0.049	1.000	4.919	0.102	0.0927	0.1030	0.089	2.102	0.879	0.726	0.664	0.007	0.100	0.990
S47	0.496	2.440	0.049	0.049	1.000	4.919	0.201	0.1267	0.1459	0.192	2.978	0.957	0.208	0.524	0.010	0.215	1.069
S48	0.496	2.440	0.048	0.049	1.021	4.919	0.301	0.1497	0.1759	0.280	3.590	0.931	0.313	0.440	0.012	0.309	1.029
S49	0.495	2.438	0.101	0.050	0.495	4.925	0.050	0.0777	0.0807	0.046	1.614	0.924	1.047	0.742	0.002	0.049	0.976
S50	0.495	2.438	0.101	0.050	0.495	4.925	0.203	0.1367	0.1471	0.191	2.942	0.940	0.540	0.529	0.006	0.203	0.998
S51	0.495	2.438	0.101	0.050	0.495	4.925	0.399	0.1807	0.1992	0.348	3.984	0.874	0.978	0.440	0.008	0.370	0.928
S52	0.493	2.443	0.100	0.100	1.000	4.955	0.101	0.1337	0.1437	0.093	1.437	0.920	0.553	0.972	0.010	0.107	1.0642
S53	0.493	2.443	0.100	0.100	1.000	4.955	0.201	0.1667	0.1825	0.181	1.825	0.901	0.622	0.708	0.011	0.203	1.013
S54	0.493	2.443	0.100	0.100	1.000	4.955	0.399	0.2147	0.2412	0.353	2.412	0.887	0.638	0.614	0.016	0.397	0.995
S55	0.495	2.442	0.099	0.200	2.020	4.933	0.202	0.2187	0.2464	0.162	1.232	0.803	0.882	1.259	0.035	0.220	1.0924
S56	0.495	2.442	0.099	0.200	2.020	4.933	0.301	0.2507	0.2870	0.263	1.435	0.874	0.499	0.975	0.035	0.339	1.1276
S57	0.495	2.442	0.099	0.200	2.020	4.933	0.398	0.2767	0.3208	0.363	1.604	0.912	0.325	0.743	0.033	0.445	1.117
S58	0.495	2.440	0.200	0.049	0.245	4.929	0.101	0.1067	0.1091	0.099	2.227	0.983	0.428	0.644	0.002	0.102	1.011
S59	0.495	2.440	0.200	0.049	0.245	4.929	0.202	0.1447	0.1497	0.197	3.055	0.978	0.417	0.511	0.003	0.203	1.007
S60	0.495	2.440	0.200	0.049	0.245	4.929	0.397	0.2017	0.2124	0.389	4.335	0.981	0.258	0.440	0.005	0.403	1.016
S61	0.495	2.442	0.201	0.100	0.498	4.933	0.050	0.1137	0.1165	0.047	1.165	0.932	1.310	0.814	0.002	0.049	0.973
S62	0.495	2.442	0.201	0.100	0.498	4.933	0.201	0.1797	0.1879	0.192	1.879	0.957	0.522	0.699	0.006	0.204	1.015
S63	0.495	2.442	0.201	0.100	0.498	4.933	0.399	0.2327	0.2472	0.369	2.472	0.925	0.778	0.605	0.009	0.392	0.983
S64	0.495	2.446	0.199	0.202	1.015	4.941	0.201	0.2377	0.2531	0.171	1.253	0.850	1.199	1.230	0.019	0.202	1.0041
S64F	0.495	2.446	0.199	0.202	1.015	4.941	0.201	0.2387	0.2542	0.173	1.258	0.863	1.085	1.222	0.019	0.205	1.0178
S65	0.495	2.446	0.199	0.202	1.015	4.941	0.299	0.2627	0.2818	0.241	1.395	0.806	1.485	1.031	0.020	0.280	0.9374
S66	0.495	2.446	0.199	0.202	1.015	4.941	0.400	0.2917	0.3155	0.338	1.562	0.845	1.086	0.797	0.019	0.382	0.9564
											AVG	0.922				AVG	0.999
											STD	0.051				STD	0.041
											MIN	0.766				MIN	0.921
											MAX	1.015				MAX	1.128
											n	61				n	61

APPENDIX E

APPENDIX: E1

Crump weir without dividing walls - test WMOD3-1s. Total data set in Appendix F2.

$l_1 = 0{,}999$ m $\qquad l_2 = 3{,}005$ m $\qquad$ P = 0,268 m $\qquad$ t = 0,098 m

$Q_m = 0{,}080\ m^3/s \qquad h_x = 0{,}1129$ m

The general formula.

$$Q = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_d l H^{1,5} \text{ and } C_d = 1{,}163\left(1-\frac{0{,}0003}{h}\right)^{1,5}$$

Determination of H_x and Q_{cx}

$Q_{cx} = Q_1 + Q_2$

Assuming horizontal water surface and total energy line across the width of the weir. This implies :

$H_1 = H_x$; $H_2 = H_x - t$

and, $h_1 = h_x$; $h_2 = h_x - t$

$$Q_{cx} = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_{d1}l_1 H_x^{1,5} + \left(\frac{2}{3}\right)^{1,5}\sqrt{g}C_{d2}l_2\left(H_x - t\right)^{1,5}$$

with, $C_{d1} = 1{,}163\left(1-\dfrac{0{,}0003}{h_x}\right)^{1,5}$ and $C_{d2} = 1{,}163\left(1-\dfrac{0{,}0003}{h_x - t}\right)^{1,5}$

First Iteration

Assume approach velocity in front of the entire weir, v_x, = 0 m/s initially.

$\Rightarrow H_x = h_x = 0{,}1129$ m

$$\therefore C_{d1} = 1{,}163\left(1-\frac{0{,}0003}{0{,}1129}\right)^{1,5} = 1{,}1584 \text{ and } C_{d2} = 1{,}163\left(1-\frac{0{,}0003}{0{,}1129-0{,}098}\right)^{1,5} = 1{,}1281$$

$$\text{and, } Q_{cx} = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}\times 1{,}1584\times 0{,}999\times 0{,}1129^{1,5} + \left(\frac{2}{3}\right)^{1,5}\sqrt{g}\times 1{,}1281\times 3{,}005\times(0{,}1129-0{,}098)^{1,5}$$

$$= 0{,}0748 + 0{,}0105 = 0{,}0854\text{m}^3/\text{s}$$

$$v_x = \frac{Q_{cx}}{A} = \frac{Q_{cx}}{(l_1+l_2)\times(P+h_x)} = \frac{0{,}0854}{(0{,}999+3{,}005)\times(0{,}268+0{,}1129)} = 0{,}05597 \text{ m/s}$$

$$\therefore H_x = h_x + \frac{v_x^2}{2g} = 0{,}1129 + \frac{(0{,}05597)^2}{2g} = 0{,}1131\text{m}$$

Second Iteration

Repeat with $H_x = 0{,}1131$m

$$Q_{cx} = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}\times 1{,}1584\times 0{,}999\times 0{,}1131^{1,5} + \left(\frac{2}{3}\right)^{1,5}\sqrt{g}\times 1{,}1281\times 3{,}005\times(0{,}1131-0{,}098)^{1,5}$$

$$= 0{,}0750 + 0{,}0107 = 0{,}0857\text{m}^3/\text{s}$$

$$v_x = \frac{Q_{cx}}{A} = \frac{Q_{cx}}{(l_1+l_2)\times(P+h_x)} = \frac{0{,}0857}{(0{,}999+3{,}005)\times(0{,}268+0{,}1129)} = 0{,}0562 \text{ m/s}$$

$$H_x = h_x + \frac{v_x^2}{2g} = 0{,}1129 + \frac{(0{,}0562)^2}{2g} = 0{,}1131\text{m}$$

Third and further iterations

Continue until H_x and Q_{cx} remain constant from one iteration to the next. After the final iteration :

$H_x = 0{,}1131m$

and, $Q_{cx} = 0{,}086m^3/s$

APPENDIX: E2

Crump weir without dividing walls - test WMOD3-1s: improved discharge calculation technique. Total data set in Appendix F2.

Determination of $Q_{\Delta H}$

$H_x = 0{,}1131$m as determined in **Appendix: E1.**

$$Q_{\Delta H} = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}\,1{,}163\left[\left(1-\frac{0{,}0003}{h_x}\right)^{1,5} l_1\left(H_x-\Delta H\right)^{1,5}+\left(1-\frac{0{,}0003}{h_x-t}\right)^{1,5} l_2\left(H_x-t-\Delta H\right)^{1,5}\right]$$

While for test WMOD3-1: $\frac{H_x}{t} = 1{,}154$

$$\Rightarrow \frac{\Delta H}{H_x} = -0{,}0132\frac{H_x}{t} + 0{,}0304$$

$$\frac{\Delta H}{0{,}1131} = -0{,}0132\frac{0{,}1131}{0{,}098} + 0{,}0304$$

$\Delta H = 0{,}0017$m

$$\therefore Q_{\Delta H} = \left(\frac{2}{3}\right)^{1,5}\sqrt{g}\,1{,}1584\times 0{,}999(0{,}1131-0{,}0017)^{1,5}$$

$$+\left(\frac{2}{3}\right)^{1,5}\sqrt{g}\,1{,}1281\times 3{,}005(0{,}1131-0{,}098-0{,}0017)^{1,5}$$

$$Q_{\Delta H} = 0{,}0733 + 0{,}0089 = 0{,}0823\,m^3/s$$

APPENDIX: E3

Thin-plate weir without dividing walls - test S37: discharge calculated with the IMFT formula. Total data set in Appendix F3.

$l_1 = 0{,}740$ m $\quad$ $l_2 = 2{,}196$ m $\quad$ P = 0,206 m $\quad$ t = 0,201 m

$Q_m = 0{,}199\ m^3/s$ $\quad$ $h_x = 0{,}2447$ m

The general formula,

$$Q = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{H_x}{P}\right) l\, H_x^{3/2}$$

Determination of H_x and Q_{cx}

$Q_{cx} = Q_1 + Q_2$

Assuming horizontal water surface and total energy line across the width of the weir. This implies :

$H_1 = H_x$; $H_2 = H_x - t$

and, $h_1 = h_x$; $h_2 = h_x - t$

$$Q_{cx} = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{H_x}{P}\right) l_1\, H_x^{3/2} + \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{H_x - t}{P + t}\right) l_2\, (H_x - t)^{3/2}$$

First Iteration

Assume approach velocity in front of the entire weir, v_x, = 0 m/s initially.

$\Rightarrow H_x = h_x = 0{,}2447$ m

$$\therefore Q_{cx} = \frac{2}{3} \times \sqrt{2g} \times \left(0{,}627 + 0{,}018 \times \frac{0{,}2447}{0{,}206}\right) 0{,}740 \times (0{,}2447)^{3/2}$$

$$+ \frac{2}{3} \times \sqrt{2g} \times \left(0{,}627 + 0{,}018 \times \left(\frac{0{,}2447 - 0{,}201}{0{,}2447 + 0{,}206}\right)\right) \times 2{,}196 \times (0{,}2447 - 0{,}201)^{3/2}$$

$$= 0{,}1715 + 0{,}0372 = 0{,}2088 \text{ m}^3/\text{s}$$

$$v_x = \frac{Q_{cx}}{A} = \frac{Q_{cx}}{(l_1 + l_2)(P + h_x)} = \frac{0{,}2088}{(0{,}740 \times 2{,}196)(0{,}206 + 0{,}2447)} = 0{,}1578 \text{ m/s}$$

$$\therefore H_x = h_x + \frac{v_x^2}{2g} = 0{,}2447 + \frac{(0{,}1578)^2}{2g} = 0{,}2460\text{m}$$

Second Iteration

Repeat with $H_x = 0{,}2460$m

$$Q_{cx} = \frac{2}{3}\sqrt{2g} \times \left(0{,}627 + 0{,}018\frac{0{,}246}{0{,}206}\right) 0{,}740 \times (0{,}2460)^{3/2}$$

$$+ \frac{2}{3}\sqrt{2g} \times \left(0{,}627 + 0{,}018\left(\frac{0{,}246 - 0{,}201}{0{,}206 + 0{,}201}\right)\right) 2{,}196 \times (0{,}2460 - 0{,}201)^{3/2}$$

$$= 0{,}1729 + 0{,}0389 = 0{,}2118 \text{ m}^3/\text{s}$$

$$v_x = \frac{Q_{cx}}{A} = \frac{Q_{cx}}{(l_1 + l_2)(P + h_x)} = \frac{0{,}2118}{(0{,}740 \times 2{,}196)(0{,}206 + 0{,}2447)} = 0{,}1601 \text{ m/s}$$

$$H_x = h_x + \frac{v_x^2}{2g} = 0{,}2447 + \frac{(0{,}1601)^2}{2g} = 0{,}2460\text{m}$$

Third and further iterations

Continue until H_x and Q_{cx} remain constant from one iteration to the next. After the final iteration :

$H_x = 0,2460m$

and, $Q_{cx} = 0,212m^3/s$

APPENDIX: E4

Thin-plate weir without dividing walls - test S37: discharge calculated with improved technique using IMFT discharge formula. Total data set in Appendix F3.

Determination of $Q_{\Delta H}$

$H_x = 0{,}2460$m as determined in **Appendix E3.**

$$Q_{\Delta H} = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{(H_x - \Delta H)}{P}\right) l_1 \, (H_x - \Delta H)^{3/2}$$
$$+ \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{(H_x - \Delta H - t)}{P + t}\right) l_2 \, (H_x - \Delta H - t)^{3/2}$$

While for test S37: $\dfrac{H_x}{t} = 1{,}224$

$$\Rightarrow \frac{\Delta H}{H_x} = -0{,}0046\frac{H_x}{t} + 0{,}0161$$

$$\frac{\Delta H}{0{,}2460} = -0{,}0046\frac{0{,}2460}{0{,}2010} + 0{,}0161$$

$$\Delta H = 0{,}0026 \text{ m}$$

$$\therefore Q_{\Delta H} = \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\frac{(0{,}2460 - 0{,}0026)}{0{,}206}\right) \times 0{,}740 \times (0{,}2460 - 0{,}0026)^{3/2}$$
$$+ \frac{2}{3}\sqrt{2g}\left(0{,}627 + 0{,}018\left(\frac{(0{,}2460 - 0{,}0026 - 0{,}201)}{0{,}206 + 0{,}201}\right)\right) \times 2{,}196 \times (0{,}2460 - 0{,}0026 - 0{,}201)^{3/2}$$

$$Q_{\Delta H} = 0{,}1702 + 0{,}0357 = 0{,}2059 \text{ m}^3\text{/s}$$

APPENDIX: E5

Thin-plate weir without dividing walls - test S37: discharge calculated with DWAF formula. Total data set in Appendix F4.

$l_1 = 0{,}740$ m $l_2 = 2{,}196$ m   P = 0,206 m   t = 0,201 m

$Q_m = 0{,}199\ m^3/s$ $h_x = 0{,}2447$ m

The general formula.

$$Q = 1{,}777\, l\, C_p\, (H + 0{,}001)^{3/2}$$

with,

$$C_p = 1{,}000 + 0{,}11\left(\frac{H}{H+P}\right)^{1{,}24} \quad \text{if} \quad H/P \le 3{,}4$$

$$C_p = 1{,}145\left(\frac{P}{H+P}\right)^{0{,}09} \quad \text{if} \quad 3{,}4 < H/P \le 200$$

$$C_p = 0{,}926 \quad \text{if} \quad H/P > 200$$

Determination of H_x and Q_{cx}

$Q_{cx} = Q_1 + Q_2$

Assuming horizontal water surface and total energy line across the width of the weir. This implies :

$H_1 = H_x$; $H_2 = H_x - t$

and, $h_1 = h_x$; $h_2 = h_x - t$

$$Q_{CX} = 1{,}777\, l_1\, C_{P1}\, (H_x + 0{,}001)^{3/2} + 1{,}777\, l_2\, C_{P2}\, (H_x - t + 0{,}001)^{3/2}$$

First Iteration

Assume approach velocity in front of the entire weir, v_x, = 0 m/s initially.

$\Rightarrow H_x = h_x = 0{,}2447$ m

and, $\dfrac{H_x}{P} = \dfrac{0{,}2447}{0{,}206} = 1{,}188 < 3{,}4$

$$\Rightarrow C_{P1} = 1{,}000 + 0{,}11\left(\frac{H_x}{H_x + P}\right)^{1,24} = 1{,}000 + 0{,}11\left(\frac{0{,}2447}{0{,}2447 + 0{,}206}\right)^{1,24} = 1{,}0516$$

$$\text{and, } C_{P2} = 1{,}000 + 0{,}11\left(\frac{H_x - t}{(H_x - t) + (P + t)}\right)^{1,24} = 1{,}000 + 0{,}11\left(\frac{0{,}2447 - 0{,}201}{0{,}2447 + 0{,}206}\right)^{1,24}$$

$$= 1{,}0061$$

$$\therefore Q_{cx} = 1{,}777 \times 0{,}740 \times 1{,}0516 \times (0{,}2447 + 0{,}001)^{1,5}$$

$$+ 1{,}777 \times 2{,}196 \times 1{,}0061 \times (0{,}2447 - 0{,}201 + 0{,}001)^{1,5}$$

$$= 0{,}1684 + 0{,}0371 = 0{,}2055 \text{ m}^3/\text{s}$$

$$v_x = \frac{Q_{cx}}{A} = \frac{Q_{cx}}{(l_1 + l_2)(P + h_x)} = \frac{0{,}2055}{(0{,}740 \times 2{,}196)(0{,}206 + 0{,}2447)} = 0{,}1553 \text{ m/s}$$

$$\therefore H_x = h_x + \frac{v_x^2}{2g} = 0{,}2447 + \frac{(0{,}1553)^2}{2g} = 0{,}2459\text{m}$$

Second Iteration

Repeat with $H_x = 0{,}2459$m

$$C_{p1} = 1{,}000 + 0{,}11\left(\frac{0{,}2459}{0{,}2459 + 0{,}206}\right)^{1{,}24} = 1{,}0517$$

$$\text{and, } C_{p2} = 1{,}000 + 0{,}11\left(\frac{0{,}2459 - 0{,}201}{0{,}2459 + 0{,}206}\right)^{1{,}24} = 1{,}0063$$

$$Q_{cx} = 1{,}777 \times 0{,}740 \times 1{,}0517 \times (0{,}2459 + 0{,}001)^{1{,}5}$$

$$+ 1{,}777 \times 2{,}196 \times 1{,}0063 \times (0{,}2459 - 0{,}201 + 0{,}001)^{1{,}5}$$

$$= 0{,}1697 + 0{,}0387 = 0{,}2083 \text{ m}^3/\text{s}$$

$$v_x = \frac{Q_{cx}}{A} = \frac{Q_{cx}}{(l_1 + l_2)(P + h_x)} = \frac{0{,}2083}{(0{,}740 \times 2{,}196)(0{,}206 + 0{,}2447)} = 0{,}1574 \text{ m/s}$$

$$H_x = h_x + \frac{v_x^2}{2g} = 0{,}2447 + \frac{(0{,}1574)^2}{2g} = 0{,}2460\text{m}$$

Third and further iterations

Continue until H_x and Q_{cx} remain constant from one iteration to the next. After the final iteration:

$H_x = 0{,}2460$m

and, $Q_{cx} = 0{,}209\text{m}^3/\text{s}$

APPENDIX: E6

Thin-plate weir without dividing walls - test S37: discharge calculated with improved technique using DWAF discharge formula. Total data set in Appendix F4.

Determination of $Q_{\Delta H}$

$H_x = 0{,}2460$m as determined in **Appendix E5.**

$$Q_{\Delta H} = 1{,}777\left[C_{P1} l_1 (H_x - \Delta H + 0{,}001)^{1.5} + C_{P2} l_2 (H_x - t - \Delta H + 0{,}001)^{1.5}\right]$$

While for test S37: $\frac{H_x}{t} = 1{,}224$

$$\Rightarrow \frac{\Delta H}{H_x} = -0{,}0091\frac{H_x}{t} + 0{,}0173$$

$$\frac{\Delta H}{0{,}2460} = -0{,}0091\frac{0{,}2460}{0{,}201} + 0{,}0173$$

$\Delta H = 0{,}0015$m

$$C_{P1} = 1{,}000 + 0{,}11\left(\frac{H_x - \Delta H}{H_x - \Delta H + P}\right)^{1.24}$$

$$= 1{,}000 + 0{,}11\left(\frac{0{,}2460 - 0{,}0015}{0{,}2460 - 0{,}0015 + 0{,}206}\right)^{1.24} = 1{,}0516$$

$$C_{P2} = 1{,}000 + 0{,}11\left(\frac{H_x - \Delta H - t}{(H_x - \Delta H - t) + (P + t)}\right)^{1.24}$$

$$= 1{,}000 + 0{,}11\left(\frac{0{,}2460 - 0{,}0015 - 0{,}201}{0{,}2460 - 0{,}0015 + 0{,}206}\right)^{1.24} = 1{,}0061$$

$$\therefore Q_{\Delta H} = 1{,}777 \times 0{,}740 \times 1{,}0516(0{,}2460 - 0{,}0015 + 0{,}001)^{1.5}$$
$$+ 1{,}777 \times 2{,}196 \times 1{,}0061(0{,}2460 - 0{,}201 - 0{,}0015 + 0{,}001)^{1.5}$$

$$Q_{\Delta H} = 0{,}1682 + 0{,}0368 = 0{,}2050\,m^3/s$$

APPENDIX F

APPENDIX: F1

Crump weir without dividing walls; flows confined to the low notch. Standard as well as improved calculation techniques.

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WMOD1-1s	1.597	2.416	0.269	0.097	0.020	0.0356	0.0356	0.021	0.367	1.051	0.0327	0.0172	0.0006	0.020	1.024
WMOD1-1s	1.597	2.416	0.269	0.097	0.050	0.0641	0.0642	0.051	0.662	1.023	0.0148	0.0172	0.0011	0.050	0.996
WMOD1-1s	1.597	2.416	0.269	0.097	0.080	0.0874	0.0876	0.082	0.903	1.021	0.0135	0.0172	0.0015	0.080	0.994
WMOD1-2s	1.597	2.416	0.176	0.097	0.020	0.0353	0.0353	0.021	0.364	1.038	0.0249	0.0172	0.0006	0.020	1.012
WMOD1-2s	1.597	2.416	0.176	0.097	0.050	0.0640	0.0642	0.051	0.661	1.022	0.0143	0.0172	0.0011	0.050	0.996
WMOD1-2s	1.597	2.416	0.176	0.097	0.080	0.0874	0.0877	0.082	0.904	1.023	0.0150	0.0172	0.0015	0.080	0.997
WMOD1-3s	1.597	2.416	0.085	0.097	0.020	0.0345	0.0346	0.020	0.357	1.006	0.0038	0.0172	0.0006	0.020	0.980
WMOD1-3s	1.597	2.416	0.085	0.097	0.050	0.0639	0.0643	0.051	0.663	1.025	0.0163	0.0172	0.0011	0.050	0.999
WMOD1-3s	1.597	2.416	0.085	0.097	0.080	0.0870	0.0877	0.082	0.904	1.023	0.0151	0.0172	0.0015	0.080	0.997
WMOD2-3s	1.230	2.792	0.089	0.098	0.020	0.0432	[illegible]	0.022	0.439	1.087	0.0482	0.0172	0.0007	0.021	1.049
WMOD2-3s	1.230	2.792	0.089	0.098	0.050	0.0758	[illegible]	0.051	0.777	1.018	0.0128	0.0172	0.0013	0.050	0.993
WMOD2-2s	1.230	2.792	0.173	0.098	0.020	0.0435	[illegible]	0.022	0.444	1.097	0.0596	0.0172	0.0007	0.021	1.068
WMOD2-2s	1.230	2.792	0.173	0.098	0.050	0.0764	0.0765	0.051	0.781	1.027	0.0175	0.0172	0.0013	0.050	1.000
WMOD2-1s	1.230	2.792	0.268	0.098	0.020	0.0430	0.0430	0.022	0.442	1.077	0.0542	0.0172	0.0007	0.021	1.059
WMOD2-1s	1.230	2.792	0.268	0.098	0.050	0.0761	0.0762	0.051	0.777	1.020	0.0119	0.0172	0.0013	0.050	0.992
WMOD3-1s	0.999	3.005	0.268	0.098	0.020	0.0468	0.0468	0.020	0.478	0.994	-0.0041	0.0172	0.0008	0.019	0.968
WMOD3-1s	0.999	3.005	0.268	0.098	0.050	0.0883	0.0884	0.052	0.902	1.036	0.0230	0.0172	0.0015	0.050	1.009
WMOD3-2s	0.999	3.005	0.185	0.098	0.020	0.0475	0.0475	0.020	0.485	1.017	0.0110	0.0172	0.0008	0.020	0.991
WMOD3-2s	0.999	3.005	0.185	0.098	0.050	0.0879	0.0880	0.051	0.898	1.029	0.0191	0.0172	0.0015	0.050	1.003
WMOD3-3s	0.999	3.005	0.103	0.098	0.020	0.0467	0.0468	0.020	0.477	0.992	-0.0054	0.0172	0.0008	0.019	0.967
WMOD3-3s	0.999	3.005	0.103	0.098	0.050	0.0878	0.0880	0.051	0.898	1.030	0.0193	0.0172	0.0015	0.050	1.003
WMOD4-2s	0.804	3.200	0.183	0.098	0.005	0.0216	0.0216	0.005	0.221	0.992	-0.0054	0.0172	0.0004	0.005	0.966
WMOD4-2s	0.804	3.200	0.183	0.098	0.010	0.0351	0.0351	0.010	0.358	1.036	0.0231	0.0172	0.0006	0.010	1.009
WMOD4-2s	0.804	3.200	0.183	0.098	0.015	0.0449	0.0449	0.015	0.458	1.002	0.0012	0.0172	0.0008	0.015	0.976
WMOD4-2s	0.804	3.200	0.183	0.098	0.020	0.0551	0.0551	0.020	0.563	1.023	0.0153	0.0172	0.0009	0.020	0.997
WMOD4-3s	0.804	3.200	0.103	0.098	0.010	0.0347	0.0347	0.010	0.354	1.018	0.0120	0.0172	0.0006	0.010	0.992
WMOD4-3s	0.804	3.200	0.103	0.098	0.020	0.0548	0.0549	0.020	0.560	1.016	0.0105	0.0172	0.0009	0.020	0.990
WMOD5-2s	0.672	3.332	0.183	0.099	0.005	0.0244	0.0244	0.005	0.247	0.998	-0.0015	0.0172	0.0004	0.005	0.972
WMOD5-2s	0.672	3.332	0.183	0.099	0.010	0.0406	0.0406	0.011	0.410	1.079	0.0492	0.0172	0.0007	0.011	1.051
WMOD5-2s	0.672	3.332	0.183	0.099	0.015	0.0517	0.0517	0.016	0.522	1.036	0.0232	0.0172	0.0009	0.015	1.009
WMOD5-2s	0.672	3.332	0.183	0.099	0.020	0.0630	[illegible]	0.021	0.637	1.047	0.0300	0.0172	0.0011	0.020	1.020
WMOD5-3s	0.672	3.332	0.093	0.099	0.005	0.0246	0.0246	0.005	0.249	1.010	0.0069	0.0172	0.0004	0.005	0.984
WMOD5-3s	0.672	3.332	0.093	0.099	0.010	0.0393	0.0393	0.010	0.397	1.027	0.0178	0.0172	0.0007	0.010	1.001
WMOD5-3s	0.672	3.332	0.093	0.099	0.015	0.0516	0.0516	0.016	0.522	1.034	0.0217	0.0172	0.0009	0.015	[illegible]
WMOD5-3s	0.672	3.332	0.093	0.099	0.020	0.0625	0.0626	0.021	0.632	1.035	0.0228	0.0172	0.0011	0.020	[illegible]

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WMOD6-3s	0.670	3.332	0.121	0.071	0.010	0.0385	0.0385	0.010	0.555	0.993	0.0181	0.0172	0.0007	0.010	1.001
WMOD6-3s	0.670	3.332	0.121	0.071	0.020	0.0619	0.0619	0.020	0.862	1.017	-0.0007	0.0172	0.0011	0.019	0.973
WMOD6-2s	0.670	3.332	0.211	0.071	0.010	0.0394	0.0394	0.010	0.543	1.028	-0.0049	0.0172	0.0007	0.010	0.967
WMOD6-2s	0.670	3.332	0.211	0.071	0.020	0.0612	0.0612	0.020	0.873	0.999	0.0110	0.0172	0.0011	0.020	0.991
C1	1.197	1.780	0.171	0.107	0.050	0.0779	0.0782	0.052	0.731	1.040	0.0261	0.0172	0.0013	0.050	1.014
C2	1.197	1.780	0.171	0.107	0.072	0.0982	0.0986	0.073	0.923	1.020	0.0128	0.0172	0.0017	0.071	0.993
									AVG	1.027				AVG	1.001
									STD	0.024				STD	0.023
									MIN	0.992				MIN	0.966
									MAX	1.097				MAX	1.060
									n	41				n	41

APPENDIX: F2

Crump weir without dividing walls, flow over all crests. Standard as well as improved calculation techniques.

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	[illegible] (m)	[illegible] (m)	P (m)	t (m)	Q (m³/s)	h (m)	H (m)	Q (m³/s)	[illegible]	Q/Q	[illegible]	[illegible]	ΔH (m)	Q (m³/s)	[illegible]
WMOD1-1s	1.597	2.416	0.269	0.097	0.120	0.1100	0.1112	0.125	1.146	1.039	0.0179	0.0153	0.0017	0.121	1.005
WMOD1-1s	1.597	2.416	0.269	0.097	0.150	0.1219	0.1224	0.154	1.262	1.028	0.0120	0.0137	0.0017	0.150	0.997
WMOD1-1s	1.597	2.416	0.269	0.097	0.177	0.1306	0.1313	0.180	1.353	1.017	0.0078	0.0125	0.0016	0.175	0.989
WMOD1-2s	1.597	2.416	0.176	0.097	0.120	0.1107	0.1113	0.125	1.148	1.042	0.0187	0.0152	0.0017	0.121	1.008
WMOD1-2s	1.597	2.416	0.176	0.097	0.150	0.1222	0.1231	0.156	1.269	1.040	0.0177	0.0136	0.0017	0.151	1.009
WMOD1-2s	1.597	2.416	0.176	0.097	0.177	0.1308	0.1319	0.182	1.360	1.029	0.0131	0.0124	0.0016	0.177	1.001
WMOD1-3s	1.597	2.416	0.085	0.097	0.120	0.1088	0.1101	0.122	1.135	1.017	0.0080	0.0154	0.0017	0.118	0.984
WMOD1-3s	1.597	2.416	0.085	0.097	0.150	0.1204	0.1222	0.153	1.260	1.023	0.0104	0.0138	0.0017	0.149	0.992
WMOD1-3s	1.597	2.416	0.085	0.097	0.177	0.1287	0.1309	0.179	1.350	1.011	0.0055	0.0126	0.0016	0.174	0.983
WMOD2-3s	1.230	2.792	0.089	0.098	0.080	0.1029	0.1035	0.083	1.056	1.036	0.0163	0.0165	0.0017	0.080	1.000
WMOD2-3s	1.230	2.792	0.089	0.098	0.120	0.1213	0.1224	0.125	1.249	1.040	0.0160	0.0139	0.0017	0.121	1.004
WMOD2-3s	1.230	2.792	0.089	0.098	0.150	0.1311	0.1326	0.153	1.353	1.017	0.0073	0.0125	0.0017	0.148	0.986
WMOD2-3s	1.230	2.792	0.089	0.098	0.177	0.1385	0.1404	0.176	1.433	0.992	-0.0024	0.0115	0.0016	0.171	0.965
WMOD2-2s	1.230	2.792	0.173	0.098	0.080	0.1041	0.1044	0.085	1.065	1.057	0.0248	0.0163	0.0017	0.082	1.020
WMOD2-2s	1.230	2.792	0.173	0.098	0.120	0.1229	0.1235	0.128	1.260	1.063	0.0240	0.0138	0.0017	0.123	1.027
WMOD2-2s	1.230	2.792	0.173	0.098	0.150	0.1327	0.1335	0.155	1.362	1.034	0.0132	0.0124	0.0017	0.150	1.003
WMOD2-2s	1.230	2.792	0.173	0.098	0.177	0.1406	0.1416	0.180	1.445	1.014	0.0061	0.0113	0.0016	0.175	0.987
WMOD2-1s	1.230	2.792	0.268	0.098	0.080	0.1034	0.1036	0.083	1.057	1.038	0.0173	0.0164	0.0017	0.080	1.002
WMOD2-1s	1.230	2.792	0.268	0.098	0.120	0.1219	0.1222	0.124	1.247	1.036	0.0136	0.0139	0.0017	0.120	1.000
WMOD2-1s	1.230	2.792	0.268	0.098	0.150	0.1334	0.1339	0.156	1.366	1.042	0.0162	0.0124	0.0017	0.151	1.010
WMOD2-1s	1.230	2.792	0.268	0.098	0.177	0.1402	0.1408	0.177	1.437	1.000	-0.0003	0.0114	0.0016	0.172	0.972
WMOD3-1s	0.999	3.005	0.268	0.098	0.080	0.1129	0.1131	0.086	1.154	1.071	0.0251	0.0152	0.0017	0.082	1.028
WMOD3-1s	0.999	3.005	0.268	0.098	0.120	0.1294	0.1297	0.125	1.324	1.045	0.0156	0.0129	0.0017	0.121	1.009
WMOD3-1s	0.999	3.005	0.268	0.098	0.150	0.1397	0.1402	0.155	1.430	1.031	0.0115	0.0115	0.0016	0.150	1.000
WMOD3-1s	0.999	3.005	0.268	0.098	0.177	0.1487	0.1493	0.183	1.524	1.032	0.0117	0.0103	0.0015	0.178	1.005
WMOD3-2s	0.999	3.005	0.185	0.098	0.080	0.1128	0.1131	0.086	1.154	1.071	0.0251	0.0152	0.0017	0.082	1.028
WMOD3-2s	0.999	3.005	0.185	0.098	0.120	0.1292	0.1297	0.125	1.324	1.045	0.0156	0.0129	0.0017	0.121	1.008
WMOD3-2s	0.999	3.005	0.185	0.098	0.150	0.1397	0.1404	0.155	1.433	1.036	0.0136	0.0115	0.0016	0.151	1.005
WMOD3-2s	0.999	3.005	0.185	0.098	0.177	0.1483	0.1493	0.182	1.523	1.031	0.0117	0.0103	0.0015	0.178	1.003
WMOD3-3s	0.999	3.005	0.103	0.098	0.080	0.1121	0.1126	0.085	1.149	1.059	0.0216	0.0152	0.0017	0.081	1.016
WMOD3-3s	0.999	3.005	0.103	0.098	0.120	0.1283	0.1292	0.124	1.319	1.034	0.0133	0.0130	0.0017	0.120	0.998
WMOD3-3s	0.999	3.005	0.103	0.098	0.150	0.1383	0.1396	0.153	1.424	1.020	0.0086	0.0116	0.0016	0.148	0.988
WMOD3-3s	0.999	3.005	0.103	0.098	0.177	0.1472	0.1489	0.181	1.519	1.024	0.0104	0.0103	0.0015	0.176	0.997

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	Q_m (m³/s)	h_m (m)	H_x (m)	Q_{sc} (m³/s)	H_x/t	Q_m/Q_{sc}	Δ H/Hx Calc	Δ H/Hx Fit	Δ H (m)	Q_{ict} (m³/s)	Q_{ict}/Q_m
WMOD4-2s	0.804	3.200	0.183	0.098	0.050	0.1015	0.1016	0.053	1.037	1.052	0.0211	0.0167	0.0017	0.051	1.012
WMOD4-2s	0.804	3.200	0.183	0.098	0.080	0.1193	0.1196	0.085	1.220	1.067	0.0207	0.0143	0.0017	0.082	1.020
WMOD4-2s	0.804	3.200	0.183	0.098	0.120	0.1353	0.1358	0.126	1.386	1.047	0.0151	0.0121	0.0016	0.121	1.010
WMOD4-2s	0.804	3.200	0.183	0.098	0.150	0.1451	0.1458	0.154	1.488	1.028	0.0095	0.0107	0.0016	0.150	0.997
WMOD4-2s	0.804	3.200	0.183	0.098	0.177	0.1527	0.1536	0.178	1.567	1.007	0.0023	0.0097	0.0015	0.174	0.980
WMOD4-3s	0.804	3.200	0.103	0.098	0.050	0.1020	0.1022	0.053	1.043	1.069	0.0279	0.0166	0.0017	0.051	1.026
WMOD4-3s	0.804	3.200	0.103	0.098	0.080	0.1202	0.1207	0.088	1.232	1.098	0.0305	0.0141	0.0017	0.084	1.051
WMOD4-3s	0.804	3.200	0.103	0.098	0.120	0.1351	0.1360	0.126	1.388	1.051	0.0173	0.0121	0.0016	0.122	1.014
WMOD4-3s	0.804	3.200	0.103	0.098	0.150	0.1451	0.1464	0.156	1.494	1.039	0.0142	0.0107	0.0016	0.151	1.008
WMOD4-3s	0.804	3.200	0.103	0.098	0.172	0.1503	0.1518	0.172	1.549	1.003	0.0023	0.0099	0.0015	0.168	0.975
WMOD5-2s	0.672	3.332	0.183	0.099	0.050	0.1083	0.1084	0.053	1.095	1.062	0.0183	0.0159	0.0017	0.050	1.010
WMOD5-2s	0.672	3.332	0.183	0.099	0.080	0.1243	0.1246	0.085	1.258	1.061	0.0177	0.0138	0.0017	0.081	1.013
WMOD5-2s	0.672	3.332	0.183	0.099	0.120	0.1394	0.1399	0.123	1.413	1.029	0.0092	0.0117	0.0016	0.119	0.992
WMOD5-2s	0.672	3.332	0.183	0.099	0.150	0.1500	0.1507	0.155	1.522	1.031	0.0103	0.0103	0.0016	0.150	1.000
WMOD5-2s	0.672	3.332	0.183	0.099	0.177	0.1564	0.1573	0.175	1.588	0.989	-0.0038	0.0094	0.0015	0.170	0.962
WMOD5-3s	0.672	3.332	0.093	0.099	0.050	0.1081	0.1083	0.053	1.094	1.059	0.0174	0.0160	0.0017	0.050	1.007
WMOD5-3s	0.672	3.332	0.093	0.099	0.080	0.1238	0.1243	0.084	1.255	1.053	0.0153	0.0138	0.0017	0.080	1.006
WMOD5-3s	0.672	3.332	0.093	0.099	0.120	0.1393	0.1402	0.124	1.416	1.037	0.0120	0.0117	0.0016	0.120	1.000
WMOD5-3s	0.672	3.332	0.093	0.099	0.150	0.1494	0.1507	0.155	1.522	1.031	0.0109	0.0103	0.0016	0.150	1.000
WMOD5-3s	0.672	3.332	0.093	0.099	0.174	0.1556	0.1572	0.175	1.588	1.004	0.0016	0.0094	0.0015	0.170	0.978
WMOD6-3s	0.670	3.332	0.121	0.071	0.050	0.0895	0.0897	0.052	1.263	1.040	0.0193	0.0137	0.0012	0.050	0.994
WMOD6-3s	0.670	3.332	0.121	0.071	0.080	0.1034	0.1038	0.083	1.463	1.038	0.0174	0.0111	0.0012	0.080	1.004
WMOD6-3s	0.670	3.332	0.121	0.071	0.120	0.1177	0.1185	0.122	1.670	1.015	0.0109	0.0083	0.0010	0.119	0.992
WMOD6-3s	0.670	3.332	0.121	0.071	0.150	0.1276	0.1288	0.152	1.814	1.015	0.0103	0.0064	0.0008	0.150	0.998
WMOD6-3s	0.670	3.332	0.121	0.071	0.177	0.1337	0.1352	0.172	1.904	0.974	-0.0059	0.0052	0.0007	0.170	0.961
WMOD6-2s	0.670	3.332	0.211	0.071	0.050	0.0893	0.0894	0.051	1.259	1.028	0.0149	0.0138	0.0012	0.049	0.982
WMOD6-2s	0.670	3.332	0.211	0.071	0.080	0.1033	0.1035	0.082	1.458	1.029	0.0146	0.0111	0.0012	0.080	0.994
WMOD6-2s	0.670	3.332	0.211	0.071	0.120	0.1181	0.1185	0.122	1.670	1.015	0.0101	0.0083	0.0010	0.119	0.992
WMOD6-2s	0.670	3.332	0.211	0.071	0.150	0.1282	0.1289	0.152	1.815	1.016	0.0103	0.0064	0.0008	0.150	0.999
WMOD6-2s	0.670	3.332	0.211	0.071	0.175	0.1347	0.1355	0.174	1.909	0.992	0.0009	0.0052	0.0007	0.171	0.979
C3	1.197	1.780	0.171	0.107	0.121	0.1302	0.1312	0.126	1.227	1.037	0.0211	0.0142	0.0019	0.122	1.006
C4	1.197	1.780	0.171	0.107	0.150	0.1428	0.1442	0.155	1.349	1.031	0.0178	0.0126	0.0018	0.150	1.003
C5	1.197	1.780	0.171	0.107	0.201	0.1626	0.1648	0.207	1.542	1.029	0.0168	0.0100	0.0017	0.203	1.007
C6	1.197	1.780	0.171	0.107	0.299	0.1941	0.1981	0.306	1.853	1.024	0.0143	0.0059	0.0012	0.302	1.011
C7	1.197	1.780	0.171	0.107	0.395	0.2205	0.2265	0.401	2.119	1.014	0.0098	0.0024	0.0005	0.399	1.009
C8	0.735	2.242	0.171	0.106	0.151	0.1615	0.1628	0.155	1.534	1.024	0.0145	0.0101	0.0016	0.151	1.002
C9	0.735	2.242	0.171	0.106	0.201	0.1807	0.1827	0.207	1.722	1.029	0.0150	0.0076	0.0014	0.203	1.010
C10	0.735	2.242	0.171	0.106	0.300	0.2124	0.2161	0.308	2.037	1.027	0.0144	0.0035	0.0008	0.305	1.019

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	Q_m (m^3/s)	h_o (m)	H_e (m)	Q_{st} (m^3/s)	H/t	Q_{st}/Q_m	ΔH/Hx Calc	ΔH/He [illegible]	[illegible]	[illegible]	[illegible]
C11	0.735	2.242	0.171	0.106	0.398	0.2391	0.2447	0.405	2.306	1.016	0.0099	-0.0001	0.0000	0.405	1.016
C12	0.479	2.498	0.171	0.107	0.201	0.1915	0.1934	0.206	1.807	1.022	0.0114	0.0065	0.0013	0.202	1.005
C13	0.479	2.498	0.171	0.107	0.299	0.2207	0.2240	0.298	2.094	0.998	0.0017	0.0027	0.0006	0.296	0.991
C14	0.479	2.498	0.171	0.107	0.396	0.2493	0.2546	0.402	2.379	1.013	0.0082	-0.0010	-0.000	0.403	1.016
C15	0.479	2.498	0.089	0.107	0.071	0.1359	0.1365	0.073	1.277	1.030	0.0130	0.0135	0.0018	0.069	0.984
C16	0.479	2.498	0.089	0.107	0.102	0.1511	0.1522	0.103	1.424	1.018	0.0095	0.0116	0.0018	0.100	0.981
C17	0.479	2.498	0.089	0.107	0.202	0.1891	0.1922	0.202	1.798	1.004	0.0047	0.0066	0.0013	0.199	0.987
C18	0.479	2.498	0.089	0.107	0.299	0.2189	0.2244	0.299	2.099	1.002	0.0038	0.0027	0.0006	0.297	0.996
C19	0.479	2.498	0.089	0.107	0.398	0.2448	0.2529	0.396	2.366	0.996	0.0010	-0.0009	-0.000	0.397	0.998
C20	0.735	2.242	0.089	0.107	0.081	0.1301	0.1310	0.085	1.225	1.048	0.0211	0.0142	0.0019	0.082	1.007
C21	0.735	2.242	0.089	0.107	0.121	0.1485	0.1501	0.124	1.404	1.026	0.0136	0.0119	0.0018	0.120	0.994
C22	0.735	2.242	0.059	0.107	0.202	0.1780	0.1813	0.202	1.696	1.002	0.0041	0.0080	0.0014	0.198	0.982
C23	0.735	2.242	0.089	0.107	0.299	0.2086	0.2145	0.301	2.007	1.006	0.0058	0.0039	0.0008	0.298	0.998
C24	0.735	2.242	0.089	0.107	0.398	0.2347	0.2434	0.398	2.277	1.000	0.0025	0.0003	0.0001	0.398	0.999
C25	1.197	1.780	0.089	0.107	0.151	0.1417	0.1443	0.155	1.350	1.024	0.0150	0.0126	0.0018	0.151	0.996
C26	1.197	1.780	0.089	0.107	0.201	0.1591	0.1629	0.202	1.524	1.006	0.0066	0.0103	0.0017	0.198	0.984
C27	1.197	1.780	0.089	0.107	0.299	0.1894	0.1960	0.299	1.834	1.001	0.0040	0.0062	0.0012	0.295	0.989
C28	1.197	1.780	0.089	0.107	0.398	0.2162	0.2260	0.399	2.115	1.002	0.0036	0.0025	0.0006	0.397	0.997
									AVG	1.020				AVG	1.000
									STD	0.022				STD	0.015
									MIN	0.974				MIN	0.961
									MAX	1.090				MAX	1.051
									n	89				n	89

APPENDIX: F3

Thin-plate weir without dividing walls; flows over both crests, discharge calculated with IMFT formula. Standard as well as improved calculation techniques.

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	l_c (m)	l_b (m)	P (m)	t (m)	Q_m (m^3/s)	h_c (m)	H_c (m)	Q_{sc} (m^3/s)	H/t	Q_{sc}/Q_m	Δ ... Calc	Δ ... Fit	Δ H (m)	Q_{ic} (m^3/s)	Q_{ic}/Q_m
S01	1.177	1.759	0.040	0.050	0.051	0.0677	0.0690	0.050	1.380	0.981	-0.0089	0.0098	0.0007	0.049	0.960
S02	1.177	1.759	0.040	0.050	0.199	0.1237	0.1319	0.193	2.638	0.968	-0.0171	0.0040	0.0005	0.191	0.961
S03	1.177	1.759	0.040	0.050	0.299	0.1507	0.1648	0.294	3.296	0.986	-0.0075	0.0009	0.0002	0.294	0.984
S04	1.177	1.759	0.091	0.050	0.050	0.0687	0.0693	0.049	1.385	0.997	-0.0014	0.0097	0.0007	0.048	0.976
S05	1.177	1.759	0.091	0.050	0.202	0.1307	0.1353	0.196	2.706	0.971	-0.0155	0.0037	0.0005	0.194	0.964
S06	1.177	1.759	0.091	0.050	0.391	0.1857	0.1977	0.394	3.954	1.007	0.0041	0.0000	0.0000	0.394	1.007
S10	1.177	1.759	0.193	0.050	0.201	0.1357	0.1379	0.200	2.758	0.996	-0.0024	0.0034	0.0005	0.198	0.989
S11	1.177	1.759	0.193	0.050	0.300	0.1667	0.1707	0.296	3.414	0.989	-0.0062	0.0004	0.0001	0.295	0.988
S12	1.177	1.759	0.193	0.050	0.397	0.1957	0.2020	0.400	4.040	1.008	0.0045	0.0000	0.0000	0.400	1.008
S13	1.174	1.761	0.193	0.100	0.101	0.1207	0.1214	0.104	1.214	1.027	0.0121	0.0105	0.0013	0.101	1.004
S14	1.174	1.761	0.193	0.100	0.202	0.1637	0.1657	0.205	1.657	1.019	0.0090	0.0085	0.0014	0.202	1.001
S15	1.174	1.761	0.193	0.100	0.396	0.2217	0.2270	0.392	2.270	0.992	-0.0039	0.0057	0.0013	0.388	0.981
S16	1.174	1.761	0.290	0.103	0.202	0.1667	0.1679	0.206	1.630	1.021	0.0096	0.0086	0.0014	0.202	1.002
S17	1.174	1.761	0.290	0.103	0.303	0.1997	0.2020	0.304	1.961	1.002	0.0009	0.0071	0.0014	0.299	0.987
S18	1.174	1.761	0.290	0.103	0.400	0.2287	0.2323	0.402	2.255	1.006	0.0030	0.0057	0.0013	0.397	0.995
S19	0.740	2.192	0.050	0.050	0.052	0.0777	0.0787	0.051	1.573	0.999	-0.0003	0.0089	0.0007	0.050	0.977
S20	0.740	2.192	0.050	0.050	0.201	0.1367	0.1435	0.200	2.870	0.994	-0.0031	0.0029	0.0004	0.199	0.988
S21	0.740	2.192	0.050	0.050	0.298	0.1627	0.1739	0.293	3.479	0.984	-0.0084	0.0001	0.0000	0.293	0.984
S22H	0.739	2.196	0.101	0.050	0.051	0.0767	0.0771	0.048	1.543	0.955	-0.0181	0.0090	0.0007	0.047	0.933
S23H	0.739	2.196	0.101	0.050	0.201	0.1407	0.1447	0.199	2.894	0.993	-0.0035	0.0028	0.0004	0.198	0.988
S24H	0.739	2.196	0.101	0.050	0.400	0.1947	0.2050	0.390	4.100	0.976	-0.0133	0.0000	0.0000	0.390	0.976
S25	0.738	2.190	0.100	0.100	0.102	0.1387	0.1399	0.107	1.399	1.053	0.0190	0.0097	0.0014	0.104	1.026
S26	0.738	2.190	0.100	0.100	0.202	0.1787	0.1820	0.208	1.820	1.032	0.0132	0.0077	0.0014	0.204	1.014
S27	0.738	2.190	0.100	0.100	0.399	0.2347	0.2432	0.399	2.432	1.002	0.0012	0.0049	0.0012	0.395	0.992
S28	0.736	2.197	0.099	0.199	0.203	0.2457	0.2482	0.225	1.247	1.110	0.0371	0.0104	0.0026	0.219	1.079
S29	0.736	2.197	0.099	0.196	0.301	0.2787	0.2830	0.322	1.422	1.071	0.0253	0.0096	0.0027	0.314	1.045

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	Q_m (m^3/s)	h_m (m)	H_c (m)	Q_{cs} (m^3/s)	H/t	Q_{cs}/Q_m	Δ [illegible] Calc	Δ [illegible]	Δ H (m)	[illegible]	[illegible]
S30	0.736	2.197	0.099	0.199	0.400	0.3077	0.3141	0.422	1.578	1.057	0.0215	0.0088	0.0028	0.413	1.034
S31	0.736	2.202	0.205	0.051	0.099	0.1047	0.1053	0.099	2.065	1.002	0.0008	0.0066	0.0007	0.098	0.987
S32	0.736	2.202	0.205	0.051	0.200	0.1457	0.1477	0.203	2.896	1.014	0.0070	0.0028	0.0004	0.202	1.009
S33	0.736	2.202	0.205	0.051	0.399	0.2047	0.2103	0.399	4.124	1.000	0.0003	0.0000	0.0000	0.399	1.000
S34	0.740	2.196	0.205	0.100	0.103	0.1397	0.1403	0.106	1.403	1.038	0.0138	0.0096	0.0014	0.104	1.011
S35	0.740	2.196	0.205	0.100	0.200	0.1807	0.1824	0.206	1.824	1.032	0.0131	0.0077	0.0014	0.203	1.013
S36	0.740	2.196	0.205	0.100	0.398	0.2397	0.2444	0.397	2.444	1.000	0.0000	0.0049	0.0012	0.393	0.990
S37	0.740	2.196	0.206	0.201	0.199	0.2447	0.2460	0.212	1.224	1.067	0.0234	0.0105	0.0026	0.206	1.037
S38	0.740	2.196	0.206	0.201	0.301	0.2817	0.2842	0.314	1.414	1.044	0.0161	0.0096	0.0027	0.306	1.018
S39	0.740	2.196	0.206	0.201	0.398	0.3117	0.3155	0.412	1.569	1.037	0.0140	0.0089	0.0028	0.403	1.014
S40	0.740	2.196	0.306	0.101	0.204	0.1837	0.1848	0.210	1.830	1.032	0.0130	0.0077	0.0014	0.206	1.013
S41	0.740	2.196	0.306	0.101	0.301	0.2167	0.2188	0.309	2.166	1.026	0.0115	0.0061	0.0013	0.305	1.012
S42	0.740	2.196	0.306	0.101	0.099	0.1387	0.1390	0.102	1.376	1.032	0.0116	0.0098	0.0014	0.100	1.005
S46	0.496	2.433	0.048	0.049	0.102	0.1057	0.1083	0.101	2.210	0.995	-0.0022	0.0059	0.0006	0.100	0.981
S47	0.496	2.433	0.048	0.049	0.202	0.1427	0.1496	0.206	3.054	[illegible]	0.0095	0.0021	0.0003	0.205	1.016
S48	0.496	2.433	0.048	0.049	0.301	0.1687	0.1801	0.300	3.675	0.998	-0.0011	0.0000	0.0000	0.300	0.998
S49	0.495	2.438	0.101	0.050	0.048	0.0817	0.0821	0.048	1.642	1.005	0.0016	0.0085	0.0007	0.047	0.981
S50	0.495	2.438	0.101	0.050	0.203	0.1457	0.1496	0.200	2.992	0.985	-0.0076	0.0023	0.0003	0.199	0.980
S51	0.495	2.438	0.101	0.050	0.397	0.2017	0.2120	0.398	4.239	1.004	0.0021	0.0000	0.0000	0.398	1.004
S52	0.495	2.437	0.101	0.101	0.102	0.1467	0.1477	0.100	1.462	0.985	-0.0050	0.0094	0.0014	0.097	0.958
S53	0.495	2.437	0.101	0.101	0.202	0.1887	0.1917	0.206	1.898	1.020	0.0076	0.0074	0.0014	0.202	1.001
S54	0.495	2.437	0.101	0.101	0.398	0.2457	0.2536	0.400	2.511	1.006	0.0026	0.0045	0.0012	0.396	0.996
S55	0.494	2.446	0.099	0.201	0.201	0.2647	0.2667	0.213	1.327	1.057	0.0171	0.0100	0.0027	0.206	1.024
S56	0.494	2.446	0.099	0.201	0.301	0.2997	0.3634	0.316	1.510	1.051	0.0165	0.0092	0.0028	0.308	1.023
S57	0.494	2.466	0.099	0.201	0.400	0.3277	0.3332	0.415	1.658	1.038	0.0133	0.0085	0.0028	0.406	1.014
S58	0.494	2.438	0.200	0.049	0.102	0.1097	0.1104	0.103	2.252	1.017	0.0070	0.0057	0.0006	0.102	1.003
S59	0.494	2.438	0.200	0.049	0.201	0.1497	0.1518	0.206	3.097	1.023	0.0113	0.0019	0.0003	0.205	1.020
S60	0.494	2.438	0.200	0.049	0.399	0.2087	0.2145	[illegible]	4.377	1.011	0.0058	[illegible]	0.0000	0.403	1.011
S61	0.492	2.438	0.200	0.100	0.050	0.1197	0.1199	0.051	1.199	1.022	0.0065	0.0106	0.0013	0.049	0.986
S62	0.492	2.438	0.200	0.100	0.203	0.1907	0.1924	0.207	1.924	1.021	0.0083	0.0073	0.0014	0.203	1.003
S63	0.492	2.438	0.200	0.100	0.400	0.2507	0.2554	0.403	2.554	1.008	0.0036	0.0043	0.0011	0.399	0.998
S64	0.495	2.434	0.199	0.201	0.200	0.2667	0.2679	0.210	1.333	1.052	0.0156	0.0100	0.0027	0.204	1.019
S65	0.495	2.434	0.199	0.201	0.301	0.3037	0.3061	0.317	1.523	1.054	0.0176	0.0091	0.0028	0.308	1.026
S66	0.495	2.434	0.199	0.201	0.400	0.3327	0.3363	0.414	1.673	1.036	0.0127	0.0084	0.0025	0.404	1.012
									AVG	1.015				AVG	1.000
									STD	0.028				STD	0.023
									MIN	0.955				MIN	0.933
									MAX	1.110				MAX	1.079
									n	60				n	60

APPENDIX: F4

Thin-plate weir without dividing walls, flows over both crests, discharge calculated with DWAF formula. Standard as well as improved calculation techniques.

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	l_1 (m)	l_2 (m)	P (m)	t (m)	Q_m (m³/s)	h_m (m)	H_e (m)	Q_{sc} (m³/s)	H/t	Q_{sc}/Q_m	Δ H/H Calc	Δ H/H Fit	Δ H (m)	Q_{ic} (m³/s)	Q_{ic}/Q_m
S01	1.177	1.759	0.040	0.050	0.051	0.0677	0.0690	0.050	1.380	0.9824	-0.0085	0.0047	0.0003	0.050	0.9724
S02	1.177	1.759	0.040	0.050	0.199	0.1237	0.1313	0.186	2.626	0.9327	-0.0377	0.0066	-0.0009	0.188	0.9445
S03	1.177	1.759	0.040	0.050	0.299	0.1507	0.1631	0.276	3.262	0.9246	-0.0448	0.0124	-0.0020	0.282	0.9454
S04	1.177	1.759	0.091	0.050	0.050	0.0687	0.0693	0.050	1.386	1.0020	0.0009	0.0047	0.0003	0.049	0.9921
S05	1.177	1.759	0.091	0.050	0.202	0.1307	0.1352	0.193	2.704	0.9573	-0.0233	-0.0073	-0.0010	0.196	0.9707
S06	1.177	1.759	0.091	0.050	0.391	0.1857	0.1971	0.384	3.942	0.9816	-0.0106	-0.0146	-0.0029	0.394	1.0068
S10	1.177	1.759	0.193	0.050	0.201	0.1357	0.1378	0.197	2.756	0.9815	-0.0101	-0.0078	-0.0011	0.200	0.9951
S11	1.177	1.759	0.193	0.050	0.300	0.1667	0.1706	0.291	3.412	0.9730	0.0154	-0.0137	-0.0023	0.299	0.9970
S12	1.177	1.759	0.193	0.050	0.397	0.1957	0.2018	0.393	4.036	0.9902	0.0056	-0.0146	-0.0029	0.403	1.0158
S13	1.174	1.761	0.193	0.100	0.101	0.1207	0.1213	0.103	1.213	1.0178	0.0080	0.0063	0.0008	0.101	1.0030
S14	1.174	1.761	0.193	0.100	0.202	0.1637	0.1656	0.202	1.656	1.0045	0.0021	0.0022	0.0004	0.201	0.9995
S15	1.174	1.761	0.193	0.100	0.396	0.2217	0.2268	0.385	2.268	0.9735	0.0138	0.0033	-0.0008	0.388	0.9798
S16	1.174	1.761	0.290	0.103	0.202	0.1667	0.1679	0.203	1.630	1.0040	0.0018	0.0025	0.0004	0.202	0.9990
S17	1.174	1.761	0.290	0.103	0.303	0.1997	0.2019	0.298	1.960	0.9832	0.0084	-0.0005	-0.0001	0.298	0.9843
S18	1.174	1.761	0.290	0.103	0.400	0.2287	0.2321	0.394	2.253	0.9862	-0.0071	-0.0032	-0.0007	0.396	0.9923
S19	0.740	2.192	0.050	0.050	0.052	0.0777	0.0787	0.052	1.574	1.0019	0.0008	0.0030	0.0002	0.051	0.9952
S20	0.740	2.192	0.050	0.050	0.201	0.1367	0.1432	0.195	2.864	0.9701	0.0152	-0.0088	-0.0013	0.199	0.9877
S21	0.740	2.192	0.050	0.050	0.298	0.1627	0.1732	0.283	3.464	0.9496	0.0279	-0.0142	-0.0025	0.290	0.9755
S22H	0.739	2.196	0.101	0.050	0.051	0.0767	0.0771	0.048	1.542	0.9584	0.0167	0.0033	0.0003	0.048	0.9497
S23H	0.739	2.196	0.101	0.050	0.201	0.1407	0.1446	0.196	2.892	0.9796	0.0104	0.0090	0.0013	0.200	0.9970
S24H	0.739	2.196	0.101	0.050	0.400	0.1947	0.2045	0.381	4.090	0.9544	0.0258	0.0146	0.0030	0.391	0.9796
S25	0.738	2.190	0.100	0.100	0.102	0.1387	0.1399	0.106	1.399	1.0433	0.0159	0.0046	0.0006	0.105	1.0302
S26	0.738	2.190	0.100	0.100	0.202	0.1787	0.1819	0.205	1.819	1.0154	0.0064	0.0007	0.0001	0.204	1.0118
S27	0.738	2.190	0.100	0.100	0.399	0.2347	0.2427	0.390	2.427	0.9784	0.0104	0.0048	0.0012	0.393	0.9859
S28	0.736	2.197	0.099	0.199	0.203	0.2457	0.2481	0.219	1.247	1.0768	0.0268	0.0060	0.0015	0.215	1.0595
S29	0.736	2.197	0.099	0.199	0.301	0.2787	0.2827	0.311	1.421	1.0333	0.0123	0.0044	0.0012	0.307	1.0213
S30	0.736	2.197	0.099	0.199	0.400	0.3077	0.3136	0.406	1.576	1.0158	0.0061	0.0030	0.0009	0.403	1.0080
S31	0.736	2.202	0.205	0.051	0.099	0.1047	0.1053	0.098	2.065	0.9889	0.0051	0.0015	0.0002	0.098	0.9948
S32	0.736	2.202	0.205	0.051	0.200	0.1457	0.1476	0.199	2.894	0.9965	0.0017	0.0080	0.0013	0.203	1.0164
S33	0.736	2.202	0.205	0.051	0.399	0.2047	0.2103	0.391	4.120	0.9810	0.0105	0.0146	0.0031	0.402	1.0086
S34	0.740	2.196	0.205	0.100	0.103	0.1397	0.1403	0.105	1.403	1.0273	[illegible]	0.0045	0.0006	0.104	1.0156
S35	0.740	2.196	0.205	0.100	0.200	0.1807	0.1823	0.203	1.823	1.0155	0.0065	0.0007	0.0001	0.203	1.0132
S36	0.740	2.196	0.205	0.100	0.398	0.2397	0.2443	[illegible]	2.443	0.9906	0.0093	0.0049	0.0012	0.394	0.9913
S37	0.740	2.196	0.206	0.201	0.199	0.2447	0.2460	[illegible]	1.224	1.0504	0.0177	0.0062	0.0015	0.205	1.0328
S38	[illegible]	2.196	0.206	0.201	0.301	0.2817	0.2841	[illegible]	1.413	1.0236	0.0088	0.0044	0.0013	0.304	1.0120
S39	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.403	[illegible]	[illegible]	0.0054	[illegible]	0.0010	0.400	1.0062

	PHYSICAL PARAMETERS				MEASURED VALUES		STANDARD CALCULATION TECHNIQUE				IMPROVED CALCULATION TECHNIQUE				
Test Number	[illegible] (m)	[illegible] (m)	P (m)	t (m)	Q_m (m³/s)	h_m (m)	H_c (m)	Q_c (m³/s)	H/t	Q_c/Q_m	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
S40	0.740	2.196	0.306	0.101	0.204	0.1837	0.1848	0.206	1.830	1.0133	0.0056	0.0006	0.0001	0.206	1.0123
S41	0.740	2.196	0.306	0.101	0.301	0.2167	0.2187	0.303	2.165	1.0060	0.0027	-0.0024	-0.0005	0.304	1.0113
S42	0.740	2.196	0.306	0.101	0.099	0.1387	0.1390	0.101	1.376	1.0192	0.0071	0.00[illegible]8	0.0007	0.100	1.0061
S46	0.496	2.433	0.048	0.049	0.102	0.1057	0.1082	0.100	2.208	0.9852	-0.0062	-0.0028	-0.0003	0.101	0.9916
S47	0.496	2.433	0.048	0.049	0.202	0.1427	0.1493	0.202	3.047	0.9975	-0.0012	-0.0104	-0.0016	0.206	1.0183
S48	0.496	2.433	0.048	0.049	0.301	0.1687	0.1793	0.290	3.659	0.9641	-0.0191	-0.0146	-0.0026	0.298	0.9911
S49	0.495	2.438	0.101	0.050	0.048	0.0817	0.0821	0.049	1.642	1.0104	0.0039	0.0024	0.0002	0.048	1.0008
S50	0.495	2.438	0.101	0.050	0.203	0.1457	0.1495	0.198	2.990	0.9729	-0.0136	-0.0099	-0.0015	0.201	0.9913
S51	0.495	2.438	0.101	0.050	0.397	0.2017	0.2116	0.390	4.232	0.9839	-0.0087	-0.0146	-0.0031	0.401	1.0104
S52	0.495	2.437	0.101	0.101	0.102	0.1467	0.1477	0.099	1.462	0.9754	-0.0084	0.0040	0.0006	0.098	0.9646
S53	0.495	2.437	0.101	0.101	0.202	0.1887	0.1916	0.202	1.897	1.0015	0.0007	0.0000	0.0000	0.202	1.0015
S54	0.495	2.437	0.101	0.101	0.398	0.2457	0.2532	0.391	2.507	0.9817	-0.0084	-0.00[illegible]5	-0.0014	0.395	0.9934
S55	0.494	2.446	0.099	0.201	0.201	0.2647	0.2666	0.207	1.326	1.0294	0.0091	0.0052	0.0014	0.203	1.0090
S56	0.494	2.446	0.099	0.201	0.301	0.2997	0.3032	0.307	1.508	1.0183	0.0062	0.0036	0.0011	0.302	1.0050
S57	0.494	2.466	0.099	0.201	0.400	0.3277	0.3329	0.400	1.656	0.9993	-0.0003	0.0022	0.0007	0.398	0.9952
S58	0.494	2.438	0.200	0.049	0.102	0.1097	0.1104	0.102	2.253	1.0020	0.0010	-0.0032	-0.0004	0.103	1.0139
S59	0.494	2.438	0.200	0.049	0.201	0.1497	0.1517	0.202	3.096	1.0055	0.0026	-0.0109	-0.0016	0.207	1.0301
S60	0.494	2.438	0.200	0.049	0.399	0.2087	0.2143	0.395	4.373	0.9910	-0.0049	-0.0146	-0.0031	0.407	1.0198
S61	0.492	2.438	0.200	0.100	0.050	0.1197	0.1199	0.051	1.199	1.0240	0.0061	0.0064	0.0008	0.050	1.0001
S62	0.492	2.438	0.200	0.100	0.203	0.1907	0.1923	0.204	1.923	1.0064	0.0019	-0.0002	0.0000	0.204	1.0050
S63	0.492	2.438	0.200	0.100	0.400	0.2507	0.2553	0.395	2.553	0.9897	-0.0053	-0.0059	-0.0015	0.400	1.0016
S64	0.495	2.434	0.199	0.201	0.200	0.2667	0.2679	0.207	1.333	1.0340	0.0105	0.0052	0.0014	0.203	1.0166
S65	0.495	2.434	0.199	0.201	0.301	0.3037	0.3060	0.310	1.522	1.0323	0.0108	0.0034	0.0011	0.307	1.0215
S66	0.495	2.434	0.199	0.201	0.400	0.3327	0.3362	0.405	1.673	1.0130	0.0047	0.0021	0.0007	0.402	1.0071
									AVG	0.9967				AVG	1.000[illegible]
									STD	0.0277				STD	0.0203
									MIN	0.9246				MIN	0.9445
									MAX	1.0768				MAX	1.0595
									n	60				n	60